GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY ANNUAL REPORT FY 88

DIRECTOR

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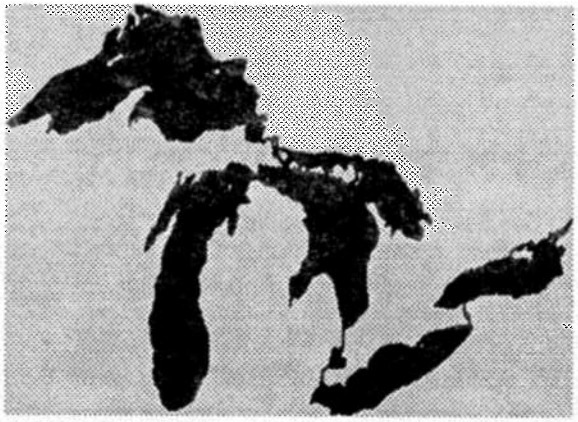
Introduction



GLERL's MISSION is to conduct integrated interdisciplinary environmental research in support of resource management and environmental services in coastal and estuarine waters, with a special emphasis on the Great Lakes. GLERL's research has traditionally been focused on investigations to improve our understanding of, and ability to predict, the biological, chemical, and physical processes occurring in natural ecosystems. Such processes affect the fate and effects of pollutants, the cycling and through-put of nutrients and energy within the food chain, water quality, and water quantity (lake levels and the hydrologic cycle), or they pose a hazard to the human populations using the natural resources of the ecosystem.

The Great Lakes Environmental Research Laboratory (GLERL), located in Ann Arbor, Michigan, is one of ten environmental laboratories operated by the National Oceanic and Atmospheric Administration (NOAA), Office of Oceanic and Atmospheric Research (OAR), through the Environmental Research Laboratories Directorate located in Boulder, Colorado.

Most of GLERL's work is conducted under NOAA's Ocean and Great Lakes Prediction Research Project and is funded under two elements of that project: Marine Ecosystems Assessment Research, and Marine Hazards and Lake Hydrology Research. In addition, GLERL cooperates closely with the U.S. Environmental Protection Agency (USEPA) on major environmental projects in the Great Lakes, which in FY 88 included the Upper Great Lakes Connecting Channels Study and the Green Bay Mass Balance Project. GLERL support for these projects was funded partially by EPA and partially from GLERL base research funds.

The products of GLERL's research are made available on a regular basis as scientific publications, NOAA Technical Series reports, computer programs and computer-based models, brochures, posters, and presentations at scientific and public meetings. These products are used by government, educational, and private organizations for purposes ranging from purely informational to actual applications and operational use. During FY 88, 43 scientific publications by GLERL authors were published, and 55 talks were presented by GLERL staff at scientific and public meetings and in local schools.

This annual report describes the significant activities and accomplishments of GLERL staff during the period October 1, 1987 - September 30, 1988. The scientific program descriptions are organized in sections according to the NOAA project elements (Marine Ecosystems Assessment, and Marine Hazards and Lake Hydrology), and major programs with outside funding (Upper Great Lakes Connecting Channels Study; Green Bay Mass Balance Study). Projects under each section are described, and the responsible scientists are listed so that those who desire more detailed information or specific technical information can reference the appropriate project scientist(s). For general information on how to obtain GLERL products, see the Outreach Section of this report.

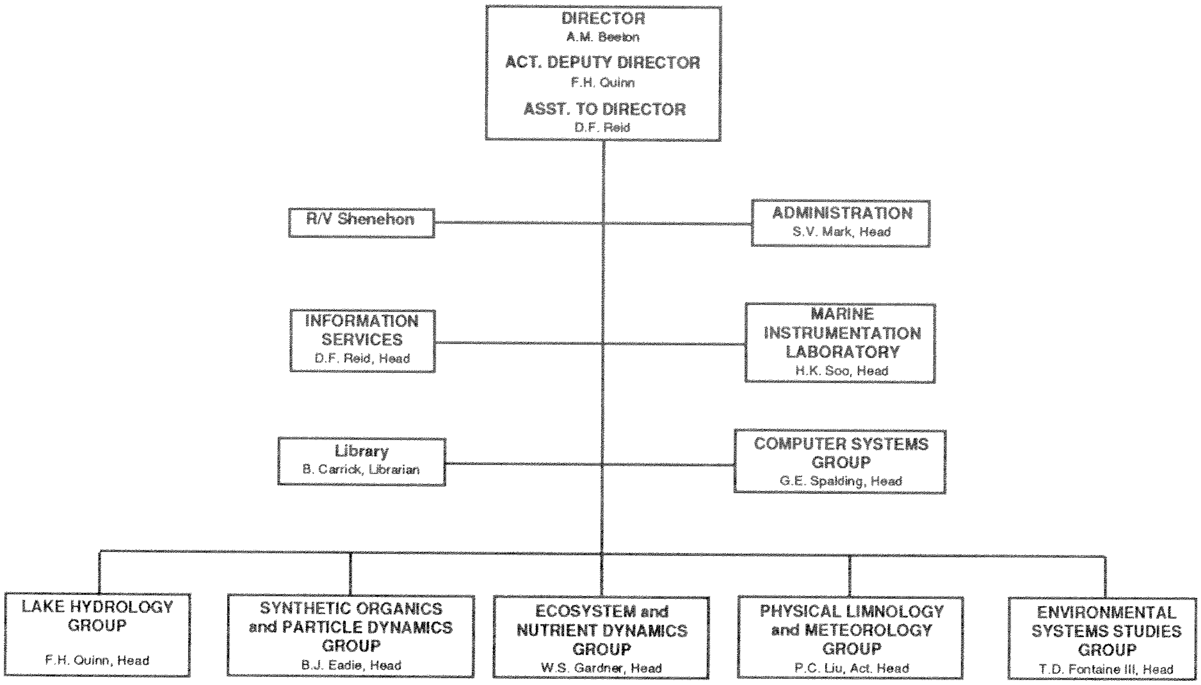
GLERL IN TRANSITION

In our FY 86-FY 87 (Combined) Annual Report, we noted that GLERL had begun a thorough review of its programmatic and functional organizations in a deliberate effort of self-examination and assessment of where GLERL should be heading as we enter the 1990s and move toward a new century. During FY 88 there were two significant occurrences related to this process.

■ Previously, GLERL's research activities were managed under eight to ten large umbrella projects. In FY 88 these umbrella programs were reorganized to reflect the individual research entities that had accumulated under each of the large umbrella projects. This change was an implementation of the Director's desire to improve the management of GLERL's research activities and of the limited resources available to support these activities.

■ At the same time, a decision was made to schedule a major planning retreat for early FY 89, to bring GLERL's scientists together in an informal atmosphere, away from daily interruptions, for the purpose of "futuring" GLERL's scientific programs and direction for the 1990s and beyond.

ORGANIZATION



GLERL is organized into five scientific groups that conduct both basic and applied research on major environmental problems and issues, plus a number of support units that provide technical, operational, and administrative assistance to the scientific staff:

Lake Hydrology Group
investigates the hydrologic and hydraulic processes that affect the water supply to, and amount of water in, the Great Lakes, The group provides improved methods of forecasting lake levels and simulating river flows, and conducts research to characterize and increase our understanding of the seasonal ice and snow cover in the Great Lakes Basin.

Synthetic Organics and Particle Dynamics Group
studies the processes that control the movement and interactions of trace contaminants in the Great Lakes and coastal marine ecosystems. The group's research increases our understanding of and ability to predict the behavior, fate, and effects of contaminants in the natural environment.

Ecosystems and Nutrient Dynamics Group

studies the ecological systems of the Great Lakes and coastal marine environments, focusing on factors and processes that affect ecological succession and control the flow of nutrients and biochemical energy (and therefore, toxics) through the food web. Group members provide and improve the information used by resource managers for making decisions that impact both water quality and living resources.

Physical Limnology and Meteorology Group

studies the physical variables that characterize a lake environment and the manner in which those characteristics change with external forces, such as wind, heat exchange, and connecting channel flows. The results of this research help understand, alleviate, or reduce the impact of physical hazards and contaminant transport on both the environment and the people who use it.

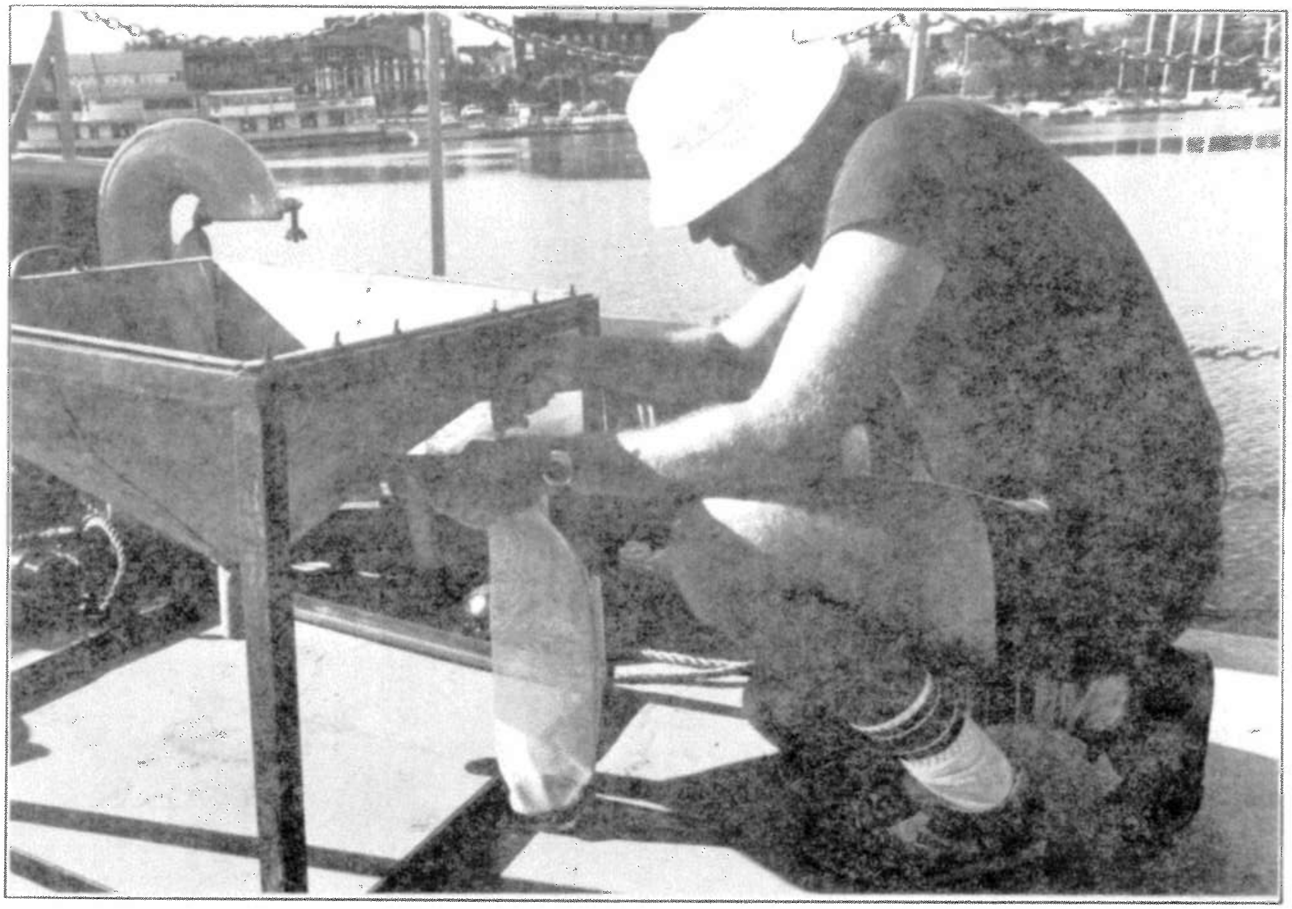
Environmental Systems Studies Group

develops models of environmental systems based on the premise that cost-effective management of our natural resources requires that we consider the competing human, economic, regulatory, and ecological factors. Group members use these models to evaluate and compare the probable costs vs. benefits of resource management plans, and to identify alternative plans that optimize the balance between competing and conflicting demands on the marine environment.

These scientific groups are supported by the following units:

- A Marine Instrumentation Laboratory, where instruments and systems for hands-on and automated field collection of data are designed, built, and maintained;
- A Computer Systems Group that maintains GLERL's in-house computer network, the interface with off-site mainframe and super computers, and provides related user support to the GLERL staff and others;
- An Information Services Group that is responsible for providing editorial and publications support to the GLERL staff, distributing GLERL publications, and responding to related information requests;
- A Library that maintains a research collection tailored to GLERL staff needs and that offers special retrieval services for materials not in the existing holdings;
- The R/V *SHENEHON*, GLERL's research vessel and the primary platform used by GLERL staff for field operations on the lakes; and
- An Administrative Office that provides personnel, budget, purchasing, and facility information and management.

Marine Ecosystem Assessment



The Marine Ecosystems Assessment research program at GLERL is designed to (1) improve our understanding of, and predictions related to, natural marine ecosystems, physical phenomena, and the effects of human-induced stresses on the ecosystems, and (2) provide a sound scientific basis for management decisions pertinent to marine resources, marine pollution, and environmentally sensitive marine activities. GLERL projects include investigations into the short- and long-term effects of human, agricultural, and industrial wastes on aquatic life and water quality; the structure and function of aquatic ecosystems and the effects of human activities on those ecosystems; the measurement, analysis, and prediction of physical phenomena such as currents and resuspension-related sedimentary fluxes and processes, which are especially important to understanding sediment-contaminant interactions.

TOXIC ORGANICS AND ENVIRONMENTAL CONTAMINATION

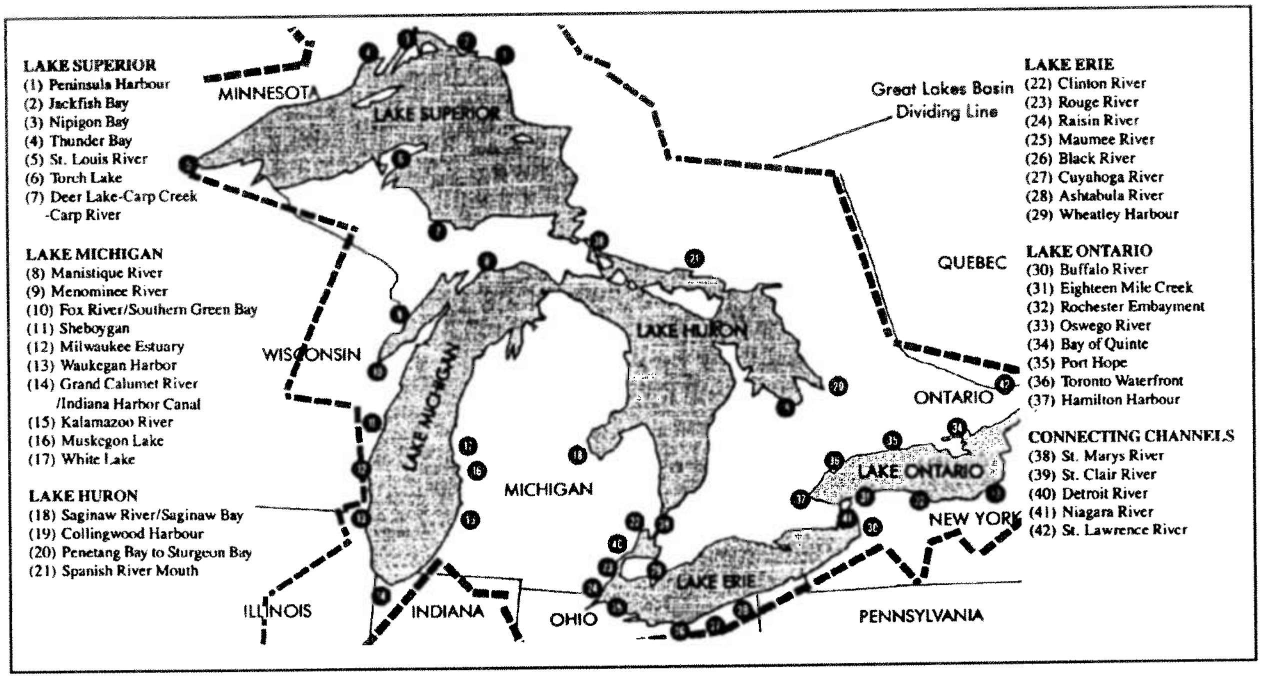


Figure 1. *Great Lakes Areas of Concern targeted by the IJC.*

More than 1,000 anthropogenic organic compounds have been identified in the Great Lakes ecosystem. More recently, contaminated sediments have become a primary focus of concern by the International Joint Commission (IJC) and the EPA (Fig. 1). GLERL has a continuing program in collaboration with the EPA, the U.S. Fish and Wildlife Service (USFWS), and various Canadian agencies to develop and improve our understanding of the processes that control the distribution, cycling and fate of organic contaminants, their toxicology, and the kinetics of biotransfer. A major focus of this research is on the association of toxic organics with suspended and deposited sediments.

The adsorption of organic contaminants onto sediment particles, followed by settling and eventual burial, is commonly the major internal process controlling the residence time and concentration of these compounds in the water column. Suspended particulate matter thus plays a vital part in the contaminant geochemistry of the Great Lakes by providing a potential mechanism for cleansing the lakes through sedimentation. Understanding the interactions between different types of suspended matter and dissolved organic contaminants, and understanding the processes that affect these interactions is critical in modeling the behavior of such contaminants in the environment.

Sediment and Resuspension Processes

Responsible Scientist: *Dr. J. A. Robbins*

Sediments play a major role in the regulation of aquatic systems and serve as a natural repository, recording present and historical changes in ecosystem status and chemical loadings. Resuspension of bottom sediments in the Great Lakes is a primary process that establishes geochemical conditions and introduces tracers, nutrients, and contaminants into the water. Direct exchanges between bottom sediments and overlying water are also important processes but remains poorly understood and are currently the subject of considerable interest in the Great Lakes and elsewhere.

GLERL's research, while focused on the Great Lakes, encompasses diverse aquatic systems and emphasizes the use of radiotracers to identify and model fundamental lake/watershed sediment transport processes. Because of their unique and often well-defined source characteristics, the relative ease and sensitivity of measurement, and because they act as built-in natural clocks, radionuclides are in common use to probe complex environmental transport processes. The major processes on which GLERL is focusing research include horizontal sediment transport, the focusing of sediments into depositional zones, sediment deposition (Fig. 2) and geochemical changes over time (diagenesis), and seasonal resuspension of sediments and associated constituents. The importance and effects of these processes in the Great Lakes and other aquatic systems are being assessed, and the relationships between system loadings and sedimentary records of tracers, contaminants and other constituents are being explored. The significance of resuspension and depositional focusing in the Great Lakes is being comprehensively examined, and fluxes related to these processes will be compared with external loads and other loss terms.

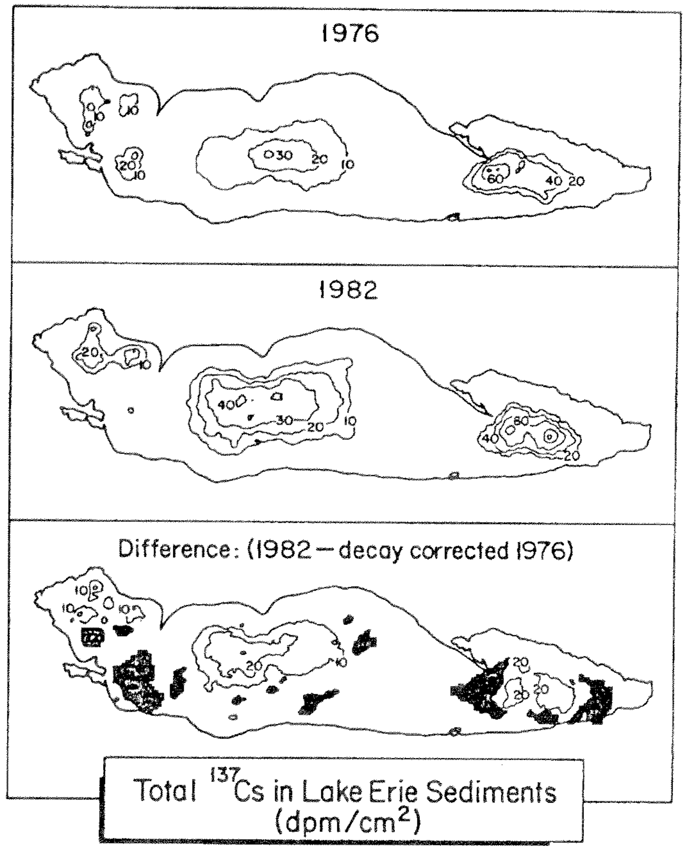


Figure 2. *Long-term changes in the storage of fallout ^{137}Cs in Lake Erie sediments. Like all particle associated contaminants, ^{137}Cs is subject to changes in horizontal distribution because of the annual cycle of resuspension and deposition. The long-term horizontal redistribution of the tracer affects the interpretation of core profiles from this and other lakes.*

Great Lakes

Sediment cores from all of the Great Lakes have been collected and analyzed over the past 15 years. They have yielded valuable information on the extent and rate of the redistribution of atmospherically derived tracers, chemical contaminants, nutrients, and other selected elements into specific depositional zones. Samples collected from Lake Erie over several years, particularly at two key sites, are currently being analyzed, and the results will be used to build post-depositional transport models. During FY 88:

- Analyses of ^{210}Pb, ^{137}Cs, and stable lead in cores collected between 1970 and 1985 at the two Lake Erie reference sites were completed (Fig. 3).
- The Rapid Steady State Mixing (RSSM) model was applied to the radionuclide data to obtain sedimentation rates, mixed depths, and focusing factors.
- A single source function for the lead profiles was developed using new noise reduction programs.
- A major resampling of the Lake Erie reference sites was conducted in September 1988 (Fig. 4) in cooperation with the Canada Centre for Inland Waters (CCIW).

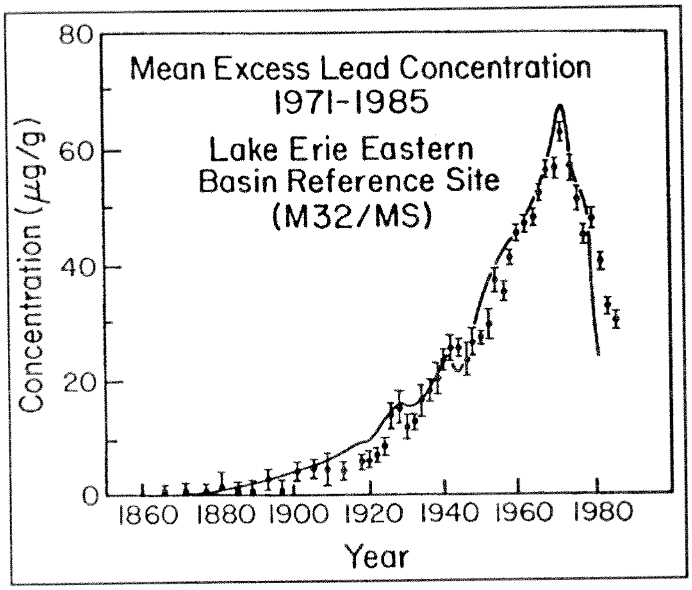


Figure 3. *Reconstruction of lead deposition in Lake Erie from sediments dated radiometrically (^{210}Pb and ^{137}Cs). The solid curve is the atmospheric loading inferred from regional use of leaded fuel additives. Many of the details in the loading are preserved in the sedimentary record as reconstructed using computer based signal-to-noise on enhancement techniques.*

Sediment cores were collected from Lake Ontario in 1987 as part of an EPA-sponsored project to determine sedimentation rates and focusing factors for mass balance calculations. Because of significant changes in recent deposition rates in this lake, new generic models will have to be developed for variable-sedimentation-rate radionuclide geochronologies. During FY 88:

- Analyses of ^{137}Cs in all cores collected in Lake Ontario for the EPA study were completed and focusing factors for depositional zones were calculated.

- Analyses of ^{210}Pb were completed in seven of ten cores collected for radiometric dating, and the RSSM model was applied to the data from each of these cores to obtain a first estimate of sedimentation rates, mixed depths, and focusing factors.

- A variable-sedimentation-rate model was developed for use with the measured radionuclide distributions in these cores.

Sediment traps are a common aquatic research tool used to obtain integrated samples of suspended sediment from the water column. GLERL has been deploying sediment traps for 10 years, primarily in Lake Michigan and to a smaller extent in Lakes Superior and Huron. Over 1,000 resuspended sediment samples have been collected and analyzed to date. Analysis of these samples has provided information on the spatial and temporal magnitudes of fluxes of particulate matter and associated nutrients and contaminants. Extensive resuspension of sediments was found in all three lakes, especially during the winter months, and mixes contaminants back into the water column.

Radionuclide measurements in trap material allow us to discriminate between resuspended and fresh components of the material collected. ^{137}Cs has been especially useful since essentially all of this fallout tracer resides in bottom sediments and reappears in the water column primarily through resuspension during the winter isothermal period. There is an overlap between GLERL's recent sediment trap sample collections and older samples collected by Argonne National Laboratory at selected sites in southern Lake Michigan. When combined, the sample sets from both sources cover a period of about 15 years. Measurement of ^{137}Cs in this suite of samples has allowed us to directly determine the removal time constants required for the development of contaminant response models.

Data generated by GLERL's long-term sediment trap studies are being compared with data obtained by CCIW from sediment traps they deployed in Lakes Erie and Ontario. A trap intercalibration experiment conducted by GLERL during 1986 and 1987 will allow us to compare and merge the data from all five lakes and produce a comprehensive Great Lakes report.

During FY 88 we accomplished the following work on sediment trap samples:

- Measurements of natural and fallout radionuclides in trap samples were completed and used to develop a model of seasonal cycling of tracers in surface waters of Lake Michigan (Fig. 5). The model includes a time variable epilimnion depth, a hypolimnetic capture process, atmospheric loadings, and resuspension terms.

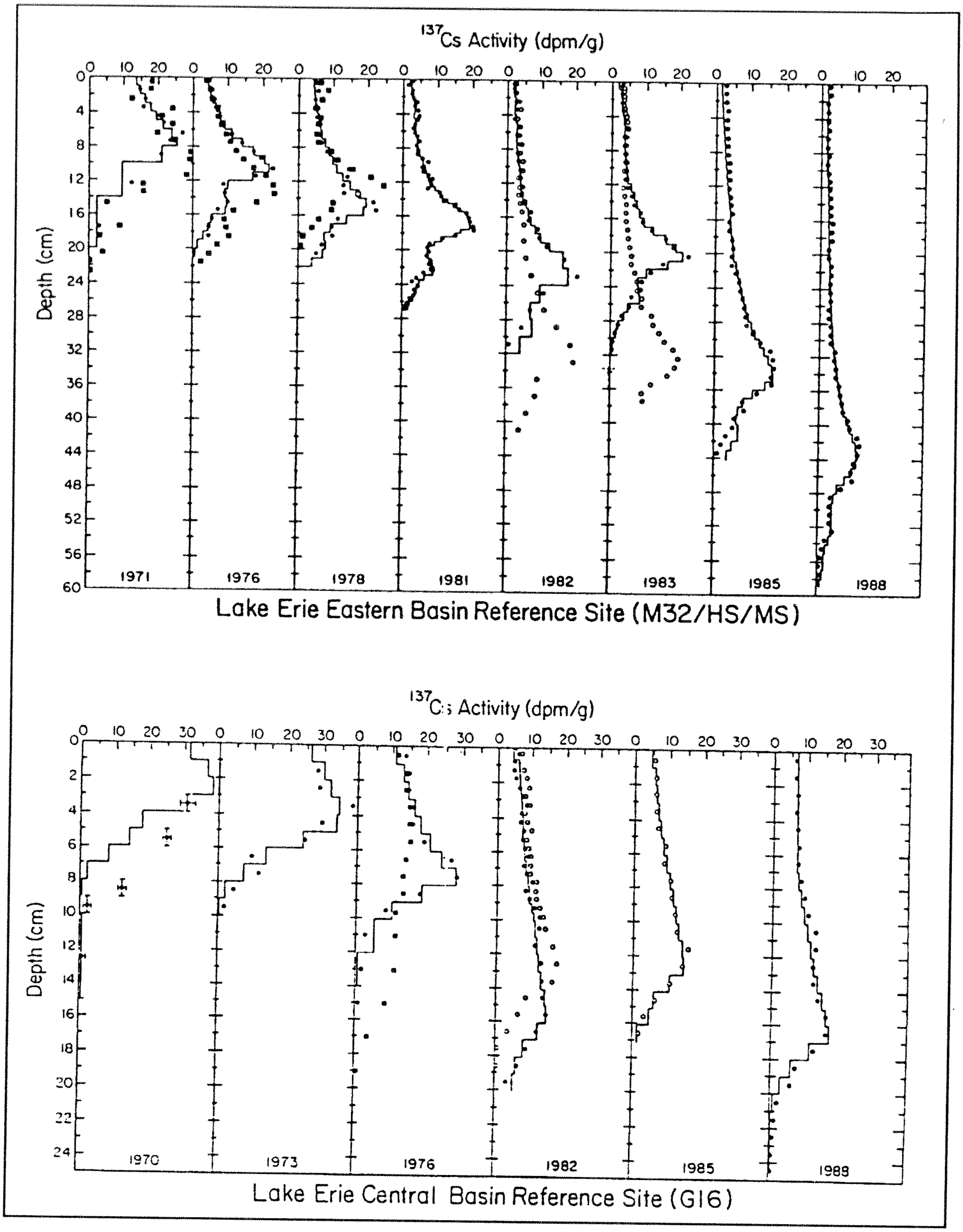


Figure 4. *Profiles of ^{137}Cs at two Lake Erie reference sites. Long-term studies of sediment distributions show the downward propagation and preservation of the fallout record. This information is useful in reconstructing the history of lake contamination as well as the present day loading and response of the lake.*

■ Very high concentrations (parts per million) of chlorinated organic contaminants were measured in material from near the surface of the water column.

■ Measurement of ^{137}Cs and ^{40}K ratios in the resuspended components of material from Lake Michigan reference sites were used to calculate decay-corrected particle-associated tracer removal rate constants for the benthic boundary layer. Rate constants were found to increase with distance offshore in the southern part of the lake, and this observation will affect the approach that must be taken for lake-status monitoring projects. The rate constants for removal of sediment-associated contaminants are on the order of decades due to coupling of bioturbation, resuspension, and burial processes.

■ Related work performed as part of the Upper Great Lakes Connecting Channels Study.

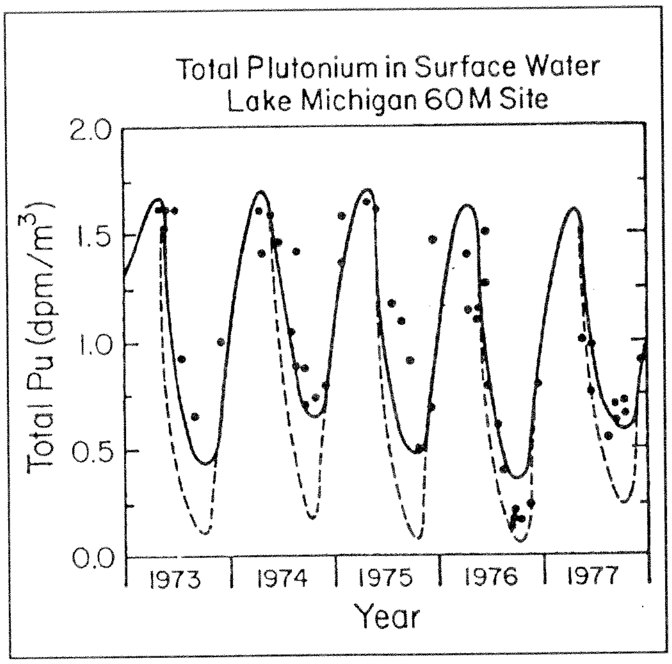


Figure 5. *Seasonal cycling of plutonium in Lake Michigan. Data collected earlier (Argonne National Laboratory) has been used to calibrate an epilimnetic tracer cycling model applicable to descriptions of generational contaminant transport. The solid curve is the least-squares optimized model prediction. The dashed curve results if the water mass transfer associated with a deepening thermocline during the summer months is ignored.*

Other Lakes

Sediments collected from a variety of freshwater systems are being analyzed for ^{7}Be, ^{137}Cs, ^{210}Pb and, in European lakes, various fallout radionuclides from the Chernobyl reactor accident. In some cases these sediments are also being analyzed by neutron activation analysis for other selected elements in order to develop a historical picture of heavy metal contamination. Systems currently being studied include: Lake George, which is situated between Michigan and Canada in the St. Marys River system below Sault St. Marie (see UGLCCS Section), Ashumet Pond, Massachusetts (with the University of Michigan), Oahe Reservoir, South Dakota (with the U. S. Geological Survey), Lake Sniardwy, Poland (with the Technical University of Wroclaw, Wroclaw, Poland), and Lake Konstanz, Germany (with the University of Konstanz, Konstanz, West Germany). Results of these studies will be used in each case for the development of integrated watershed, water, and sediment transport models characterizing the system response to loadings of radioactive tracers and analogous contaminants. During FY 88 we made the following progress on these studies:

■ Ashumet Pond: Analyses of two cores for ^{137}Cs were completed and the extent of mixing (bioturbation) was determined and characterized. This information was provided to colleagues at the University of Michigan for integration with their own data.

■ Oahe Reservoir: Analyses of ^{7}Be, ^{137}Cs were completed for two cores, and analysis of ^{210}Pb in one core was completed. The resulting data were used to develop an integrated system response model, which was provided to colleagues at the U.S. Geological Survey for integration into a larger study.

■ Lake Sniardwy: Analyses were completed of fallout radionuclides (^{137}Cs, ^{134}Cs and ^{144}Ce) in six cores received periodically over the past 3 years. In order to separate the fallout radionuclides attributable to the Chernobyl accident from those produced through nuclear testing, a computer-based model was developed and applied to the measured radionuclide profiles in these cores. The model successfully separated the Chernobyl and nuclear testing components and allowed us to make preliminary estimates of sediment mixing and tracer diffusion rates.

■ Lake Konstanz: A collaborative research project was initiated with the Department of Physics and Limnological Laboratory, University of Konstanz, West Germany following an invitation for a GLERL researcher (Dr. John Robbins) to participate in their research on Lake Konstanz.

Sediment-Associated Toxic Organics: Fate and Effects

Responsible Scientist: *Dr. P. F. Landrum*

Contaminated sediments represent the legacy of past and current discharges of contaminants, via terrestrial, atmospheric, and direct pathways, into our aquatic environments. The extent of the problem is not yet completely defined, but highly contaminated sites have been reported for both marine and freshwater systems. Contaminated sediments represent a large potential source, and in some cases the only apparent source, of contaminants to the food chain. Bottom-dwelling organisms, potentially in long-term contact with contaminated sediments, are an important food chain component and thus provide a pathway for the transfer of sediment-associated pollutants up the food chain.

Information and technical knowledge about natural processes and conditions that influence the biological availability of sediment-associated contaminants are sparse. Several questions remain: 1) What amount of sediment-associated contaminants are biologically available? 2) What levels of sediment-associated contaminants produce intoxication? 3) What are the major factors that modify the toxicity and bioavailability of sediment-associated contaminants? and 4) How long will these contaminants remain available to biota and, if necessary, what remedial options are available?

In the Great Lakes, sediment-associated pollutants are implicated as either the major source or one of the major sources of environmental problems in 41 of the 42 Areas of Concern listed by the International Joint Commission for the Great Lakes. A major part of GLERL's research on toxics is focused on the toxicology and bioavailability of contaminants from sediments in the Great Lakes and seeks to provide answers to the questions posed above.

One ongoing study involves a series of experiments on the accumulation kinetics in bottom-dwelling organisms of selected members of two classes of compounds: the polycyclic aromatic hydrocarbons (PAH) and the chlorinated hydrocarbons. These are two of the major classes of persistent contaminants found in the Great Lakes. The goal of this work is to develop useful data and relationships that will aid the regulatory agencies with the assessment of contaminated environments. Our FY 88 work resulted in the following findings:

■ A conceptual model (Fig. 6) was developed as the framework for evaluating the results of experiments to measure the accumulation kinetics for selected sediment-associated contaminants in the amphipod *Pontoporeia hoyi (P. hoyi)* .

—The model shows the pathways for the distribution of an organic contaminant among the various compartments within a simplified sediment system, including the pathways for accumulation of sediment-associated contaminants by aquatic benthos.

—An organism may accumulate compounds by ingestion of contaminated particles as well as direct uptake through the interstitial water.

—In the absence of an organism, the contaminant will achieve an equilibrium distribution between the

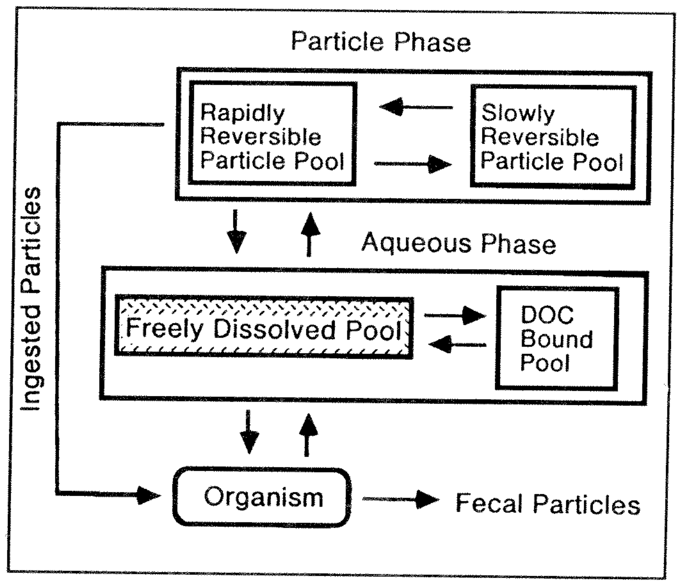


Figure 6. *Conceptual model for contaminant distribution in sediments and contaminant accumulation by benthos.*

freely dissolved pool in the interstitial water, two particle pools, and the dissolved organic matter (DOC) pool. While the processes are represented as reversible, the rates of the forward (contaminant sorption) and reverse (contaminant desorption) processes are not necessarily of the same magnitude.

■ Accumulation kinetics were measured in the amphipod *P. hoyi* and proved to be complex (Fig. 7). These kinetics are best described by a model with a biologically available contaminant pool in which some fraction of the contaminant becomes unavailable with time.

■ Measurements focusing on chemical availability revealed little or no loss of contaminants from sediments over the course of the experiments. Instead, the contaminants apparently distribute between two pools, one readily reversible and the other relatively resistant to reversal, leading to a reduction in biological availability.

■ We previously demonstrated that contaminants associated with DOC are bio-unavailable. Once the extent of biologically unavailable contaminant is accounted for, the clearance of contaminants from sediment for a single class of compounds appears to be inversely related to the hydrophobicity of the contaminant as represented by the octanol-water partition coefficient (Fig. 8).

■ The importance of particle ingestion as an accumulation route was estimated using rates of feeding, measured independently at GLERL, and an assumed assimilation efficiency of 24 percent measured for hexachlorobiphenyl (HCB), using oligochaetes. Ingestion of particles that contained the more hydrophobic compounds resulted in significant accumulation of these compounds, while the fraction of contaminant accumulated directly from the interstitial water appears to be proportional to the aqueous solubility. However,

—In an experiment to compare the slightly more hydrophobic HCB with benzo(a)pyrene (BaP), ingestion of particles was estimated to account for essentially 100 percent of the BaP accumulation, while for HCB it could only account for 50 percent. This was contrary to our general findings stated above.

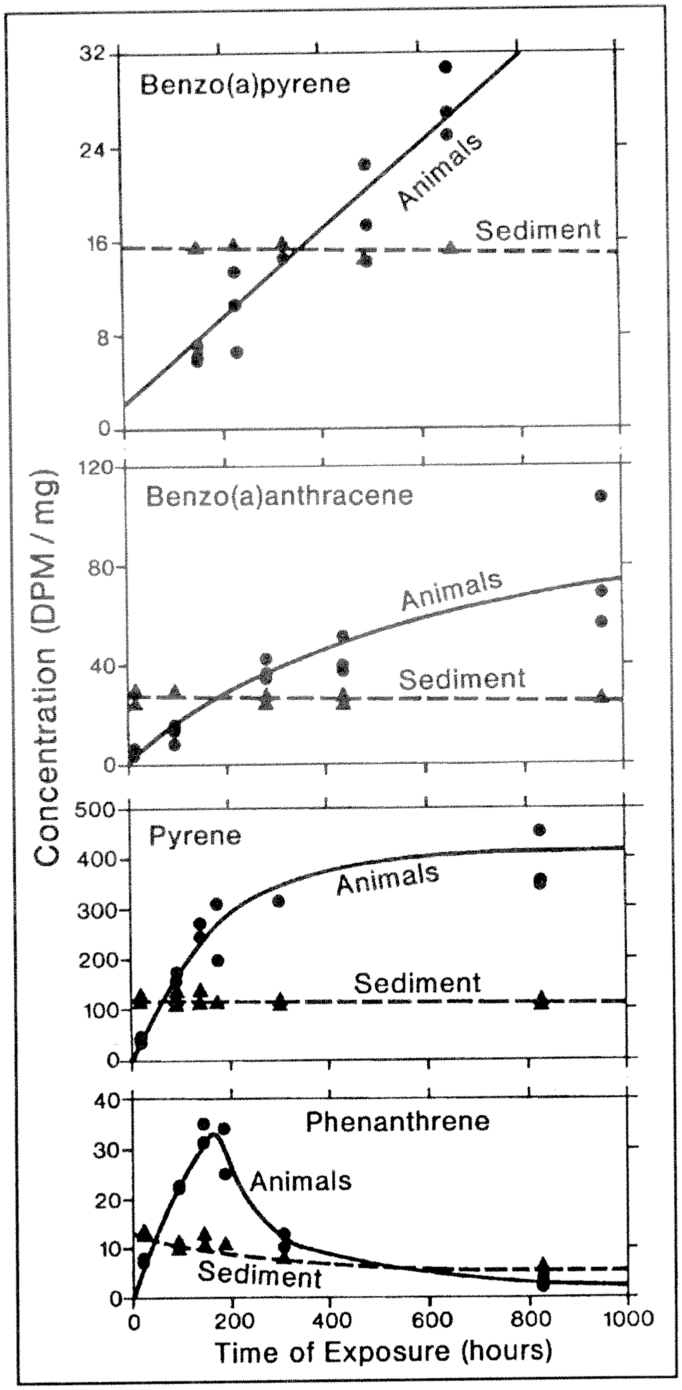


Figure 7. *Accumulation kinetics of several polycyclic aromatic hydrocarbons by the amphipod,* Pontoporia hoyi.

—Comparison of the clearances of these contaminants from sediments, measured in a dual-labeled experiment, showed that the somewhat more hydrophobic HCB is accumulated from all sources about twice as rapidly as the BaP. Since the rates of accu-

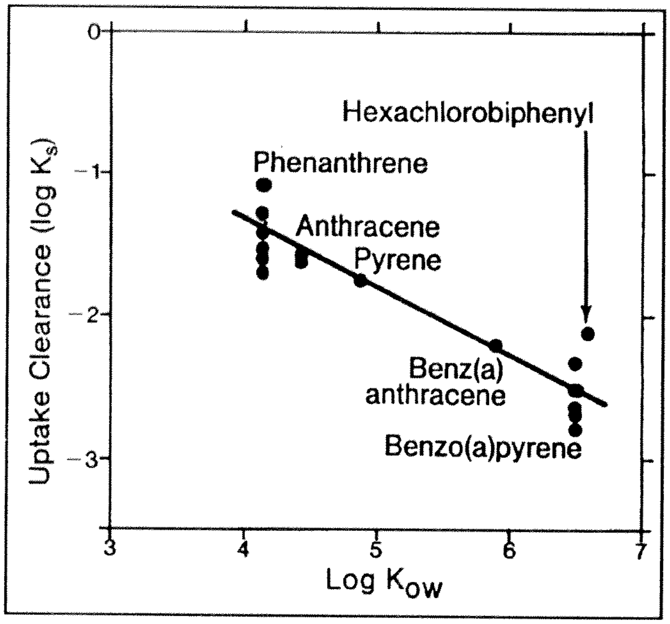


Figure 8. *Uptake clearance of polycyclic aromatic hydrocarbons and hexachlorobiphenyl as a function of the octanol:water partition coefficient, log of* K_{ow}

mulation by ingestion and assimilation are the same for the two compounds, based on our assumed assimilation efficiency, the greater rate of uptake of HCB is presumably due to more rapid desorption from particles.

Another, parallel series of experiments deals with the development of techniques (bioassays) to character ize the toxicity of materials associated with sediments. The present goal of this research is to develop two new bioassays that will be useful for assessing the location of polluted sediments primarily within the Great Lakes basin but which might be applicable to other freshwater systems. During FY 88, a series of experiments were completed:

■ Using the chlorinated hydrocarbon pesticide, endrin, a ten-day subacute solid phase toxicity test was developed based on measurements of mortality of *P. hoyi* in laboratory-dosed Lake Michigan sediments collected at 29, 45, and 100 m.

—In addition to examining the toxicity, concentrations of endrin were measured in whole sediment, interstitial water, and overlying water.

—Ancillary data on sediment organic carbon and the extent of endrin binding to dissolved organic matter were determined.

—These data will be used to evaluate the equilibrium partitioning approach suggested by USEPA for establishing sediment quality criteria. The results will also help establish the appropriateness of using *P. hoyi* to study Great Lakes sediment problems.

■ As a follow-up to previous bioavailability studies and to supplement the development of the above subacute toxicity test, *P. hoyi* were exposed in separate tests to phenanthrene and pyrene sorbed to sediments.

—In addition to measuring mortality, the concentrations of the contaminants were determined in both the sediment and organisms. Since this was performed with unlabeled compounds, the concentration in sediment interstitial water was not measurable.

—Respiration measurements of surviving organisms were made over time during the study to assess the potential for using respiration as an "effects endpoint" for *P. hoyi.*

■ Because of the success of the above laboratory studies in measuring mortality of *P. hoyi* from selected contaminants sorbed to sediments, an attempt was made to apply this assay to field-collected sediments from Saginaw Bay.

—The initial bioassay was run with sediments collected in late May 1988 and ran for 10 days. There was no mortality of *P. hoyi* above the control.

—After consultation with Dr. Mary Henry (U.S. Fish and Wildlife Service, National Fisheries Center - Great Lakes) concerning the response of the organism *Hexagenia limbata* in bioassays she conducted using Saginaw Bay sediments, we reran our *P. hoyi* bioassay for 28 days with new Saginaw Bay sediments collected in July 1988. Mortality above that of the control was found and seemed to coincide with the same site where mortality was found with *Hexageni,* by Dr. Henry.

■ Control studies of a sediment avoidance/preference assay were performed until we were certain that the assay was not producing any apparent biases due to setup and design. The assay is performed in a large aquarium in which petri dishes containing the test sediments are randomly distributed in lake water. The organisms are then introduced in equal numbers at each of the four corners and in the middle of the aquarium to obtain an equal distribution throughout the aquarium. After standing for 96 hours at 4°C, the petri dishes are removed and the sediments wet-sieved to recover and count the organisms. The sediments are then ranked by the number of organisms preferring each sediment.

—The evaluation of the control studies suggests that the assay more readily defines preferred sediments than avoided sediments. Although all the assay can really do is rank one sediment against another and against a control, this is a useful additional assay because of its ease of performance.

—When this bioassay was used with the Saginaw Bay sediments , the station that exhibited the highest mortality after 28 days was also the most preferred in the avoidance/preference assay. The absence of avoidance of the toxic sediment indicates that organisms cannot detect the presence of all compounds that may be detrimental to their existence.

In FY 87 construction was begun of an automated microcomputer-controlled system (the Gamma Scan System) to detect the toxicity of sediment-associated contaminants to benthic organisms by measuring the rate of sediment reworking in test cells. The spread and movement of a thin layer of radioisotope-spiked sediment in laboratory test cells is monitored. The movement of the spiked material is related to the rate of bioturbation by selected organisms placed in each cell. The bioturbation rate is a reflection of the health of the animal and thus, can be a sensitive indicator of the onset of toxicity. During FY 88, the following progress was made on this system development:

■ The automated hardware system was completed in March 1988.

■ The system calibration was performed and design changes made from March 1988 through May 1988.

■ Measurements of system precision were completed and showed that the reproducibility in determining the position in a horizontal scan of a line source gamma emitter is 0.001 cm in a 165 cm traverse. Similar reproducibility is obtained in vertical scans. This impressive degree of precision means that subtle changes in benthos reworking rates in response to sediment contamination are readily measurable in a matter of a few weeks.

■ Design and construction were begun of a frame that will permit sediment microcosms to be X-rayed for porosity determinations simultaneously with tracer movement measurements.

■ Once the system was considered fully functional, a 53 day test bioassay was initiated using DDT as the test toxicant and endrin as a reference toxicant (based on previous studies, see GLERL's FY 86 - FY 87 Combined Annual Report) and using *Stylodrilus heringianus* as the organism.

—The organisms in the control cells died from an unknown cause, while the cells with the DDT did not exhibit this problem.

—A control study was initiated to attempt to ascertain what may have happened to the control cells.

—The relative reworking rates at different DDT concentrations followed the results previously observed with endrin, and the automated system performed well.

Part of GLERL's toxics research program is considered investigative. During FY 88, the investigative research was varied and included studies of a potential biochemical indicator of stress and the role of lipid type in the bioaccumulation of hexachlorobiphenyl (HCB) and benzo(a)pyrene (BaP).

■ The protein composition of organisms exposed to a toxicant was monitored as a biochemical indicator of stress. For the initial studies, both *P. hoyi* and *S. heringianus* were exposed to endrin-dosed sediments.

—*S. heringianus* were exposed to 50 mg/g endrin and exhibited increasing percent protein with duration. This was due to a constant protein content on a per worm basis with apparent reductions in the energy stores and a reduction in total body weight.

Conversely, the controls had reduced percent protein with duration of exposure and an increase in protein content per worm. This was apparently a result of growth and increasing energy stores.

—The *P. hoyi* were exposed to 0.5, 1.0, and 3.0 ng/g endrin in a low organic carbon content sediment. The 3.0 ng/g concentration would be expected to elicit some mortality in *P. hoyi* in 10 days. No change in protein content was observed either on a percent basis or on an organism basis at any of the dose levels. Thus, the protein assay shows promise for use with oligochaetes but is not useful for short term assays with *P. hoyi*.

■ Experiments to identify the enrichment of HCB or BaP in a specific lipid fraction derived from a physical separation indicated that some enrichment may be occurring. However, the extent of the enrichment was not as dramatic as was anticipated. Tests were started to determine if the separation method was sufficient to separate the lipid classes.

Figure 9. *A bottom-resting flume used to determine the velocity required to initiate sediment resuspension. Water is pulled through the flume by the propeller located at the bottom of the picture. The small cylinder just behind the sail contains the electronics for a small electromagnetic current meter used to measure the current velocity in the flume. The sail is attached to a cage which protects the transmissometer. This instrument, which is mounted in the side walls of the flume, measures the amount of sediment in suspension. The shorter pressure case contains the power supply while the longer one contains the data acquisition system. The sail is used to orient the flume perpendicularly to the ambient flow.*

Development of a Bottom-Resting Flume to Determine Bottom Erosion Thresholds.

Responsible Scientist: ***Dr. Nathan Hawley***

Since many anthropogenic pollutants and other substances are adsorbed onto and transported by cohesive particulate material, it is necessary to identify and characterize the conditions causing erosion and resuspension of this material if accurate predictions are to be made of the pathways and fates of these substances. GLERL will deploy a bottom-resting flume (Fig. 9) in which the flow can be controlled to experimentally determine, in a matter of hours, the near-bottom velocity necessary to initiate sediment resuspension.

During FY 88, a series of deployments were made in Lake Superior and Lake Ontario. Although the flume operated correctly only 50 percent of the time, the results did show bottom erosion at velocities between 2 and 12 cm/s. Several modifications are being made to improve the flume's reliability.

Longterm Distributed Costs of Environmental Contamination

Responsible Scientists: ***Dr. T. D. Fontaine III; A. H. Clites***

The IJC has targeted 42 Areas of Concern in the Great Lakes basin that are in need of remedial action. In 41 of these areas, the major problem is toxic substances contamination. As the Great Lakes community mobilizes to clean up these problem areas, there has been much discussion of clean-up alternatives and related costs, but little discussion of the longterm distributed costs to the public. Distributed costs may include economic damages to sport or commercial fisheries, increased water treatment costs, public agency regulation and litigation costs, special study and monitoring costs, etc. Such costs may be large and are often overlooked because there is no inter-agency accounting system to deal with them.

Distributed costs are paid by the public either through taxation or through the loss of potential revenues. Examples of tax-based distributed costs include money collected from the public and spent on research, regulation, litigation, and clean up of contamination problems. An example of lost revenues is the reduction in potential fisheries revenues due to unacceptable contaminant levels in fish. Examples of both types of distributed costs abound in the Great Lakes and in coastal marine regions.

During FY 88, GLERL initiated a project to perform a case study of the longterm costs of pollution that are borne by the public and paid out of public funds.

- We conducted a feasibility analysis of 10 environmental sites and found that only 3 might yield enough data to conduct a reasonably complete analysis: Hudson River, NY; James River, VA; and New Bedford Harbor, MA. The James River was polluted with Kepone, while the other sites involved PCB contamination.

- Distributed cost analyses, based on available data, show a great diversity between sites (Fig. 10). For the Hudson River case, the ratio of distributed costs (government costs plus past and predicted future fishery losses) to industry costs (fines) is estimated to be 100:1. For the James River site, that ratio is 0.6:1; industry fines appear to have more than compensated for the damage done. In the case of New Bedford Harbor, the trial is pending and the ratio of distributed to industry costs will be determined by the findings and action of the courts.

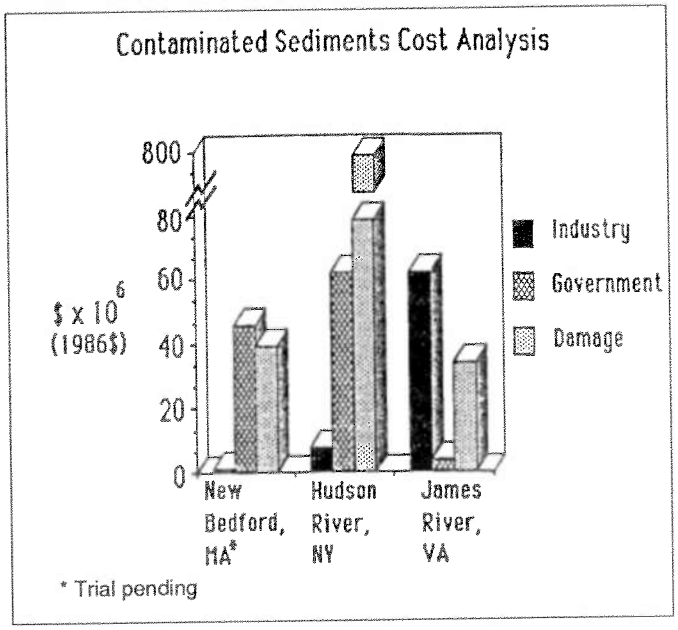


Figure 10. *Preliminary cost analyses for three case studies. Costs were separated into three categories: industry costs (fines, clean-up costs), government costs (administration, clean-up, studies, litigation), and ecosystem damage as measured by loss of fishery revenues. The latter two categories are distributed costs.*

STABLE ISOTOPES APPLIED TO LIMNOLOGY

The use of naturally abundant stable isotopes has a distinguished 40 year history of environmental biogeochemical research accomplishment, and a mass spectrometer dedicated and specially designed for this purpose is an important resource in many major environmental laboratories. All of the biogeochemically important elements (Hydrogen, Carbon, Nitrogen, Oxygen and Sulfur) have at least two stable isotopes (Table 1). Carbon, for example, has a natural abundance of 98.89 percent as C-12 (6 protons and 6 neutrons) and 1.11 percent as C-13, which has one additional neutron. Most environmental reactions favor one isotope of an element over the other isotopes of the same element and thus, stable isotope distributions can be used to identify sources and follow pathways and rates for major environmental processes. For example, the photosynthetic pathways used by land plants differ from those used by marine plants. The resulting stable carbon isotope distributions are different enough that they have been used to differentiate between terrestrial and marine sources of organic carbon found in near-shore sediments.

Exciting environmental research opportunities exist in the field of stable isotope biogeochemistry that are immediately pertinent to NOAA's and GLERL's aquatic programs. Recent advances in the instrumentation allow analysis of small (micromol) samples, opening up opportunities to examine previously unapproachable processes. An example of immediate interest is the study of carbon and nutrient cycles, which could lead to valuable insight into major primary and secondary productivity processes. After almost a year of scientific literature review and developing plans, GLERL made a major investment and commitment in FY 88 to establish an environmental stable isotope research capability.

Isotope Biogeochemistry in Limnology

Responsible Scientist: ***Dr. B. J. Eadie***

Great Lakes and coastal ecosystems are continually subject to a series of environmental stresses that are transient in nature but often lead to issues such as the biogeochemical response of systems to transient increasing or decreasing nutrient loads, man-induced changes in the carbon cycle and climate, and the introduction of toxic contaminants and their effects. GLERL's new research program focuses on these issues by studying the processes regulating the major biogeochemical cycles using analyses and modeling of the fractionation of natural stable isotopes.

Since we know from previous work that some of the Great Lakes are exhibiting major transients in carbon behavior (e.g. an increase from about 1 percent to about 30 percent $CaCO_3$ in Lake Ontario sediments over the past 30 years), the initial work will focus on carbon cycling in Lakes Ontario and Michigan, the latter of which has a very similar geochemistry to Lake Ontario but does not show an increase in $CaCO_3$.

STABLE ISOTOPES

ELEMENT	NATURAL ABUNDANCES(%)	FORM	STANDARD
^{2}H / ^{1}H	0.015 / 99.985	H_2	SMOW
^{13}C / ^{12}C	1.110 / 98.890	CO_2	PDB
^{15}N / ^{14}N	0.37 / 99.63	N_2	AIR
^{18}O / ^{16}O	0.204 / 99.759	CO_2	SMOW
^{34}S / ^{32}S	4.22 / 95.0	SO_2	Canyon Diablo Meteorite

$$\delta\,^{13}C\ (‰) = \left[\frac{^{13}C/^{12}C\ (\text{Sample})}{^{13}C/^{12}C\ (\text{Standard})} - 1\right] * 1000$$

Table 1. *The stable isotopes of the biogeochemically important elements, carbon, hydrogen, nitrogen, oxygen, and sulfur, including their natural abundances, the form (compound) used to measure the isotope ratios, and the accepted environmental standard (SMOW = standard mean ocean water; PDB = Pee Dee Belmnite; AIR = air). Also given is the definition of the "del" function, in this case defined for carbon (i.e., del C-13=...).*

Progress during FY 88 included:

■ A stable isotope mass spectrometer (SIMS) was competitively procured and installed in a specially prepared laboratory at GLERL.

—Training on the use of the SIMS, approximately 1 month split between the factory in England and GLERL, was completed.

—Machine settings were optimized for H, C, N, O, and S.

■ Sample preparation techniques were selected for organic carbon and nitrogen, and inorganic carbon and oxygen. These procedures require a multi-stage vacuum cryogenic distillation system which was constructed and tested.

■ The SIMS was intercalibrated for carbon and oxygen isotopes with facilities at the University of Michigan (Ann Arbor), Woods Hole Oceanographic Institution (Woods Hole, Massachusetts), and VG Isogas (Surrey, England).

■ Approximately 250 samples from Lake Ontario (primarily from cores) were prepared for organic and inorganic carbon isotope analyses. The concentration of carbon increases dramatically toward the surface of the cores (Fig. 11). Isotopic analysis will enable us to determine whether this is a steady-state diagenetic feature or due to changes in the delivery of carbon to the sediments.

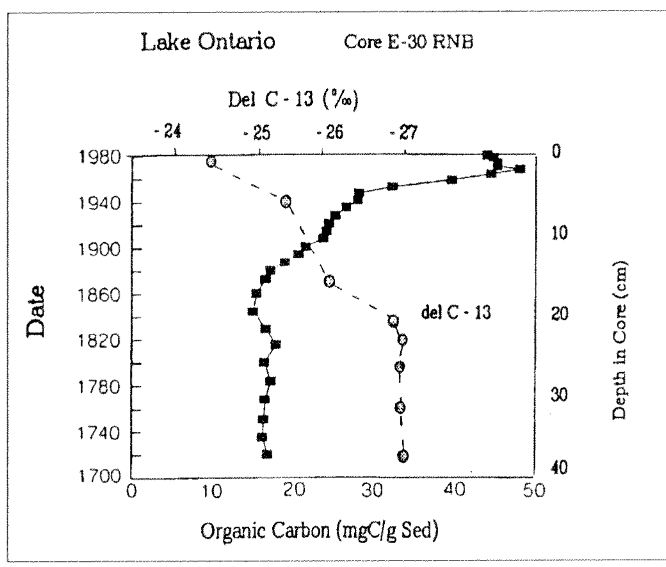


Figure 11. *The down-core distribution of organic carbon (solid squares) and del C-13 (circles) of the organic carbon in a core from Lake Ontario. See text for discussion of these results.*

ECOSYSTEM AND FOOD WEB DYNAMICS

In recent decades, profound changes in the structure and function of Great Lakes ecosystems have resulted from changing nutrient loads, invasion by foreign "exotic" organisms, and stocking of salmonine fishes. Research at GLERL, for example, has suggested that stocking of salmonine fishes in Lake Michigan has caused changes in phytoplankton and zooplankton community composition, an increase in water clarity, and a change in the carbonate- system equilibrium that has resulted in less intense calcite whitings. Changes in food webs can be affected from the bottom (i.e., nutrient changes) as well, such as we saw in the late sixties and early seventies when increased phosphorus inputs resulting from human activities caused changes in primary production and dominance by noxious blue-green algae, especially in Lake Erie.

Studies of these perturbations have raised hopes that water quality can be improved by both nutrient control and biomanipulation. However, understanding the dynamics of large aquatic ecosystems, such as the Great Lakes, requires addressing many interrelated biological, chemical, and physical processes. These processes and their interactions must be considered simultaneously if we are to gain insight toward understanding how and why the ecosystem responds as it does to anthropogenic and natural changes.

GLERL's research program focuses heavily on food web processes and the flow of materials through the ecosystem with particular, though not exclusive, emphasis on the lower end of the food chain. The need for such research is explicitly mentioned in Paragraphs 2(d), (f), and (i) of Appendix 17 of the U.S.-Canada Water Quality Agreement, as amended by protocol in 1987. Many of the problems addressed by the GLERL effort, as well as some of the approaches to these problems, were identified by a recent (1986) National Science Foundation workshop (*Basic Issues in Great Lakes Research*. Nov. 1-3, 1986, Kellogg Biological Station, Hickory Corners, MI).

Pelagic Mechanisms and the Ecology of a Perturbed Great Lake

Responsible Scientists: ***Dr. H.A. Vanderploeg; Dr. W.S. Gardner***

At present, our knowledge of many ecosystem processes is in its infancy, and our food-web models are caricatures of reality. This research on ecosystem and food web dynamics is designed to advance our knowledge of and ability to more accurately model key areas of food-web function at the lower end: phytoplankton, zooplankton, and bacteria.

Phytoplankton in the Upper Great Lakes

The role of phytoplankton in pelagic carbon cycling was a central part of GLERL's Lake Michigan Ecosystem Experiment, conducted from 1983 to 1985, and a broad outline of carbon cycling within the "classical" food web has emerged. However, this work did not attempt to determine the roles of very small phytoplankton (5 microns) in primary production, its subsequent importance to the "microbial loop" that includes various heterotrophic protozoans, or to the "classical" part of the food web that includes various crustaceans. Despite years of research on the Great Lakes, very little is known concerning typical rates and patterns of primary production in the upper Great Lakes, except for Lake Michigan, and the methodology used for what few measurements are on record are controversial and must be validated. GLERL has been conducting research to clarify the role of nanoplankton and picoplankton in the Great Lakes ecosystem, and to examine the methods and technology for determining primary production.

■ During FY 88 we completed a series of studies of the photosynthetic characteristics of phytoplankton in Lakes Michigan and Huron. The results (Fig. 12) demonstrate the occurrence of significant seasonal and vertical variations in photosynthetic-irradiance parameters and in the major end products of photosynthesis. Changes in phytoplankton community structure appear to be responsible for this variation. The data obtained from these studies provide a solid basis for comparisons between the Great Lakes and other aquatic environments.

■ The 1988 field season was the third and final year of a major study to determine the importance of autotrophic picoplankton in the Great Lakes. The samples collected over the past 3 years are providing needed information on the abundance, composition, biomass, production, growth, and grazing losses of autotrophic picoplankton communities. When completed, it will be one of the most comprehensive studies on picoplankton dynamics that has been done in any freshwater ecosystem.

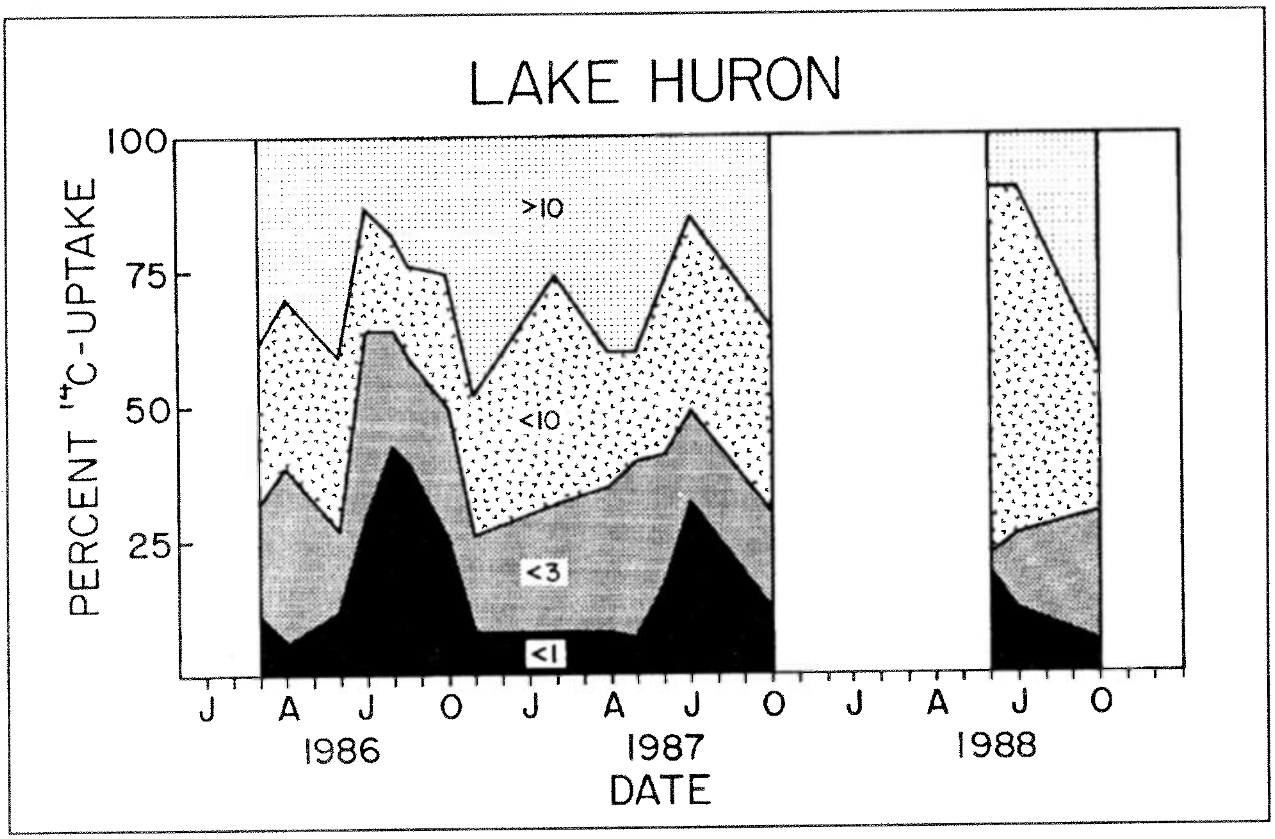


Figure 12. *Seasonal variation of ^{14}C fixation by percent contribution of various size classes of phytoplankton in Lake Huron determined by filter fractionation.*

■ Analyses of autoradiographic data from the Lake Michigan Ecosystem Experiment were completed during FY 88.

—Some diatom populations, such as *Melosira islandica* and *Fragilaria crotonensis*, had unexpectedly slow growth rates, mostly between 0.1 d^{-1} and 0.2 d^{-1}.

—Certain diatoms exhibited their highest growth rates within the deep chlorophyll layer where light is very low but nutrients are high, as contrasted to the surface mixed layer where nutrients are low but light is high.

—Very small flagellates such as *Rhodomonas minuta* exhibited very fast growth rates, 0.4-0.6 d^{-1}, throughout the year.

We believe that the slower-growing diatoms act as an important source of carbon to the benthos, whereas the faster-growing flagellates are an important source for carbon cycled within the pelagic region.

■ Analyses were completed of data from nutrient enrichment experiments conducted in Lake Superior. The results indicated that nutrient enrichment clearly produces an increase in the maximum photosynthetic rate, but has no effect on the light-harvesting ability of the cells. Thus, the photosynthetic rate of phytoplankton in Lake Superior is limited by the supply of nutrients, and the phytoplankton grow at less than their maximum intrinsic rate.

■ Analyses of samples collected in 1987 to determine the seasonal abundance of the flagellate and ciliate communities in both Lakes Huron and Michigan were completed. This was one of the first studies of flagellates and ciliates in the Upper Great Lakes. In both lakes, flagellate and ciliate abundance exhibited a strong seasonality ranging from a minimum during spring isothermal mixing to a maximum during thermal stratification.

Bacteria in Great Lakes Food Webs

Recent GLERL studies on Lake Michigan suggest that bacterial production may be fueled by organic carbon sources other than phytoplankton's release of recently fixed carbon. The fate of bacterial carbon is also unclear. If the source of dissolved organic carbon is tightly coupled to current phytoplankton production and if the bacteria are consumed by a multi-step, inefficient food web, then this heterotrophic carbon pathway is likely to be of little significance to upper trophic levels (e.g. fishes); however, it would be important to nutrient cycling. On the other hand, bacterial production could be a significant energy source if the bacteria are consumed in a short, efficient food web that makes use of allochthonous carbon or carbon from longer term storage pools. Thus, these pathways and nutrient-recycling mechanisms need further examination, which is the basis of GLERL's aquatic bacteria research.

■ A series of experiments were conducted in late FY 87 to investigate bacterial growth rates and conversion factors for thymidine uptake experiments in Lake Michigan. The resulting data analyses were completed during FY 88. Bacterial growth rates ranged from 0.1 to 0.4 d^{-1}. These measurements and conversion factors are needed to evaluate why bacterial growth rates appear to be high relative to autotrophic production rates in Lake Michigan.

■ Experiments involving the manipulation of crustacean populations showed that the crustacean population has little direct effect on bacterial and cyanobacterial populations. In companion experiments, the isotopes from labeled bacteria were traced over time in several food web components. The results show that bacteria are grazed mainly by very small organisms in the micro food web.

■ Experiments were also conducted to measure rates of grazing on bacteria and to assess the potential for bacteria to be substrate-limited. Results indicate that grazing loss rates are approximately 0.2 d^{-1} in June and 0.5 d^{-1} in August, with most bacterial grazers being organisms smaller than 2 microns. Bacterial growth rates appeared to be substrate-limited.

■ A novel approach was developed to examine the relative degree of substrate limitation of bacterial growth rates in Lake Michigan over the sampling season. Accumulation of ammonium-nitrogen in "amino-acid fortified" and "unfortified" samples of epilimnetic water, incubated in the dark, appears to provide reasonable estimates of "potential" and "actual" rates of organic-nitrogen turnover rates. The difference between these two rates is that the "labile organic nitrogen demand" provides an index of microbial organic-substrate limitation. Seasonal studies were completed using this approach and showed that bacterial growth rates have the highest degree of substrate limitation in late summer when temperatures are high and nutrient inputs are low.

■ Eight carbon-dilution experiments were conducted to estimate the carbon content of bacterial cells and to examine the potential of the nepheloid layer to supply labile organic carbon to bacteria. The bacteria contained 0.06 to 0.54 pg C μm^{-3} bacterial cell and revealed that epilimnetic bacteria, when placed in water from the nepheloid layer, grow at rates similar to those placed in epilimnetic water but accumulate more biomass in the absence of grazers. Thus bacteria from the nepheloid are expected to be charateristically larger than bacteria from the epilimnion.

Phosphorus Dynamics and Microplankton Growth in Lake Michigan

To understand phytoplankton-bacterial interactions and the seasonal succession of phytoplankton in the Great Lakes, it is necessary to understand the dynamics of phosphorus (P), the limiting nutrient in the Great Lakes, and to evaluate (1) the ability of bacteria to compete with phytoplankton for orthophosphorus and dissolved organic P, and (2) the role of silicon in affecting competition among groups of algae for P. These topics have been central themes of a multifaceted, holistic study at GLERL to define the dynamics of and mechanisms behind seasonal succession of algae in Lake Michigan. During FY 88 GLERL's research on these topics was modified, as follows:

■ Aquatic orthophosphate research was expanded to identify an "upper bound" on PO_4 concentrations in lake water. This information is important to our fundamental understanding of PO_4 uptake by algae in nature.

■ Previous schemes for calculating the kinetic constants needed to interpret phosphorus-phytoplankton-bacterial dynamics were expanded to include a refined statistical procedure for determining uptake constants in various substrate regimes and hypothetical communities based on log normal distributions. The result was an experimental-statistical design for obtaining accurate PO_4 concentration estimates.

■ In order to gain insight into how phytoplankton partition P in Lake Michigan, our research to determine the principal sources of P (organic vs. inorganic) for algae and bacteria was expanded to incorporate biochemically-based interpretations of P-transport kinetics and to evaluate the importance of alkaline phosphatase as a mediator of PO_4 uptake from dissolved organic P by algae.

Feeding Dynamics and Life-Cycle Strategies of Zooplankton

Models of phytoplankton and zooplankton succession usually distinguish between two groups of herbivorous zooplankton: copepods of the genus *Diaptomus*, and cladocerans. Cladocerans are generally filter feeders whose feeding mechanisms, life history, and reproduction are well understood. The biology of *Diaptomus* spp., which are highly selective omnivores, is not well understood. Thus, the biology of *Diaptomus* has been the focus of intense study at GLERL, the results of which will be used to develop a behaviorally based model of food selection and feeding rate that will contribute to our understanding of the seasonal succession of plankton.

■ We proposed a new theory in FY 88 to explain concentration-variable selection of different food types by zooplankton and other predators. A new paradigm was developed from microcinematographic observations and traditional feeding experiments with *Diaptomus* feeding in mixtures of algae.

—The new theory is based on the classical ethological framework of motivation and excitability of different motor patterns used to capture, handle, and ingest different food types.

—It provides a more satisfactory explanation of behavior than the commonly invoked paradigm of optimal foraging.

—It provides a suitable framework for experiments to develop predictive models of zooplankton feeding.

Our preliminary work has shown that to understand the population dynamics of calanoid copepods such as *Diaptomus* and *Limnocalanus* and their competition with cladocera, it is necessary to relate lipid accumulation patterns to feeding rate, reproduction, and temperature. Temperature appears to be a critical variable because low temperature acts as a bottleneck to reproduction but favors lipid accumulation due to a positive balance between food input and respiration. We also expect that the effect of increased temperature on the ability of *Diaptomus* to compete with cladocerans will show up as lower lipid levels during years of high temperature. During FY 88:

■ The importance of lipids in the life strategy of *Diaptomus sicilis* in Lake Michigan was documented. We found that:

—Triglyceride concentrations were observed to vary seasonally, remaining high from June through February and dropping significantly from February through May.

—Because it lives in the hypolimnion, *Diaptomus* experiences relatively high concentrations of food throughout the year, and the observed decrease in triglycerides is caused by reproductive needs (the triglycerides are used for producing eggs) rather than by food limitation.

—Ovary development, and therefore the reproductive rate, of *Diaptomus* is slowed by the low temperature of its hypolimnetic habitat.

These results suggest a new hypothesis for the observation that temperate and boreal copepods--freshwater or marine--have high lipids. That is, low temperature acts as a bottleneck to ovarian development and therefore excess food energy must go into lipid storage rather than reproduction. These results point the way for future studies to allow prediction of reproduction and survival of copepods from temperature and feeding rate data.

■ Marine zooplankton store lipids for energy reserves as either wax esters or triglycerides. Freshwater zooplankton have been thought to store only triglycerides. However, we found that the Great Lakes copepod, *Limnocalanus macrurus*, which has an oil sac resembling the wax ester (oil) sac of marine copepods, stores large quantities of wax esters. These results show for the first time that wax esters can be formed in freshwater zooplankton and explain the occurrence of these animal-produced lipids in sediments of the Great Lakes.

Feeding Strategies of Larval Anopholes, the Malaria Mosquito

GLERL has one of the few high-speed microcinematography facilities established to examine small aquatic organisms. Because of this, we were approached by research entomologists at Michigan State University to explore its usefulness for studying the behavior of the aquatic larval form of *Anopholes*, the malaria-carrying mosquito. We modified the apparatus and successfully made the first high-speed cinematic observations of the feeding behavior of larval *Anopholes* on the surface of water. The results were sufficiently promising that the National Institute of Health is funding a 5-year cooperative program through Michigan State University to conduct detailed analyses of the feeding behavior, including additional microcinematographic studies. This approach is of practical significance to understanding the ecology of this important disease vector and will also provide useful contrasts with our copepod experiments (Crustacea), so that general principles of the feeding ecology of aquatic invertebrates may be developed.

Pelagic Long-Term Trends

Responsible Scientist: *Dr. D. Scavia*

An understanding of processes leading to long-term changes in the biosphere, particularly with respect to climate and global change, is necessary if we are to develop an accurate long-term view of the environment and the ecosystems within our environment. Recent changes in Lake Michigan water quality indicators have shown that the Lake Michigan ecosystem responds in a complex and dynamic way to certain chemical, biological, and physical influences. For example, water clarity may be strongly affected by changes at the top of the food web (e.g., stocked fish) as well as from changes affecting the bottom of the food web (e.g., nutrient levels, weather). Observations of within- and cross-year variability in important ecological properties will provide both a baseline against which future changes may be compared and a method by which to detect such changes. GLERL's work in this area is focused on inter- and intra-annual variations in key water quality and on ecological properties of the Great Lakes.

■ During FY 88, the sixth year of measurement of nutrient chemistry and plankton biomass in the offshore zone of Lake Michigan was completed. The total zooplankton biomass was low in 1987 when compared to typical concentrations determined since 1982: 1.5 g m^{-2} vs. about 3 g m^{-2}.

■ The abundances of the large cladoceran, *Daphnia*, declined between 1985 and 1987 and then returned to typical post-1982 abundances of 2 g m^{-2} in 1988. Increased abundances from 1983 to 1985 were attributed to the stocking of salmonines, which preyed on and reduced the population of the plantivorous alewife (*Alosa pseudoharengus*) and thus reduced feeding pressure on *Daphnia*. The reason for the decline of *Daphnia* between 1985 and 1988 is still not clear. Such changes in zooplankton biomass may consequently affect lower members of the food web. For example, the gradual increase that has been observed in the population of heterotrophic bacteria since 1985 could be attributed to the decrease in *Daphnia*.

Benthic Ecology and Sediment Nutrient/Energy Transformations

Responsible Scientists: *Dr. W.S. Gardner; T.F. Nalepa; and M.A. Quigley*

Benthic invertebrates play several important roles in the Great Lakes ecosystem. These organisms form a vital link between primary production and fish production. They feed on material settled from the water column and are, in turn, fed upon by most species of Great Lakes fish. Thus, a good understanding of the processes and mechanisms of material transfer through the benthos will aid in predicting transfers through the rest of the system. Benthic organisms also change the nature of sediments through their constant burrowing and feeding. These activities tend to increase rates of exchange between the sediments and overlying waters, and thus, nutrients and contaminants which would otherwise be buried are reintroduced into the system.

Numerous studies in the Great Lakes have provided important information on distributions, abundances, and species composition, leading to at least some understanding of the major factors that influence benthic populations. Yet few studies have examined benthic rate functions or the dynamic interrelationships between the benthos and other ecosystem components. GLERL conducts research to study and measure the rates of benthic processes as they relate to both organisms and sediments. The information and insight gained from these studies will improve our understanding of how these two benthic components affect, and are affected by, the rest of the system.

Particular attention is paid to the benthic amphipod *Pontoporeia hoyi (P. hoyi)* because it is a major prey of Great Lakes fish. Recent emphasis has been placed on the differences in lipid and energy content among *P. hoyi* life stages in order to gain a better understanding about the role of *P. hoyi* in food web and contaminant dynamics in the Great Lakes.

During FY 88 the following work was accomplished:

■ A series of sediment trap samples were analyzed to determine the mass flux and nutritional characteristics of particles settling from the epilimnion to the benthos at a 45-m deep station in southeastern Lake Michigan.

—Flux was highest in the spring, lowest in the summer, and intermediate during autumn months.

—Organic content (ash free dry weight=AFDW) of the dried trap materials and the percentage of AFDW occurring as lipids were higher in summer than in the spring and winter.

—Hydrocarbon alkane ratios (C_{17}:C_{29}) indicated that phytoplankton input to the sediment traps peaked in the spring, shortly before *P. hoyi* showed dramatic seasonal increases in lipid content (Fig. 13).

These results support the hypothesis that *P. hoyi* receives much of its nutrition from the spring diatom bloom.

■ *P. hoyi* were fed sediment trap materials and the resulting total lipid content in the organisms was used as an index of nutritional value of the trap materials.

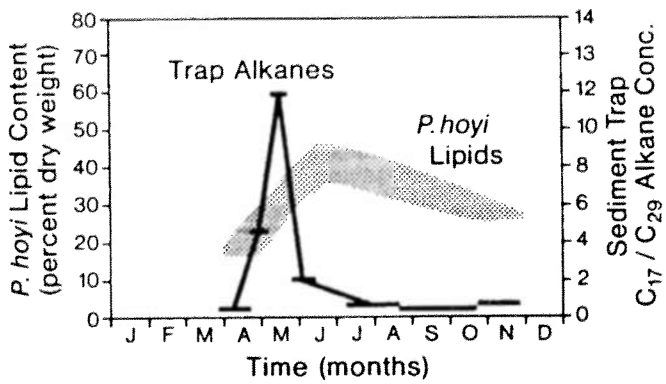


Figure 13. *Seasonal total lipid content of* P. hoyi *averaged over 2 years of collection (data taken from Gardner et al. 1985; Landrum 1988; Gauvin 1989). Also shown is the ratio of the planktonic* n-*alkane* C_{17} *to the terrestrial* n-*alkane* C_{29}. *The April-June peak is a clear signal of autochthonous carbon input. The sediment value for this ratio is 0.2.*

—Lipid content did not increase in the animals but the rate of lipid decline appeared to be related to the quality of the trap material collected throughout the season.

—The total lipid content of *P. hoyi* was found to be strongly dependent on sex and life stage (Fig. 14).

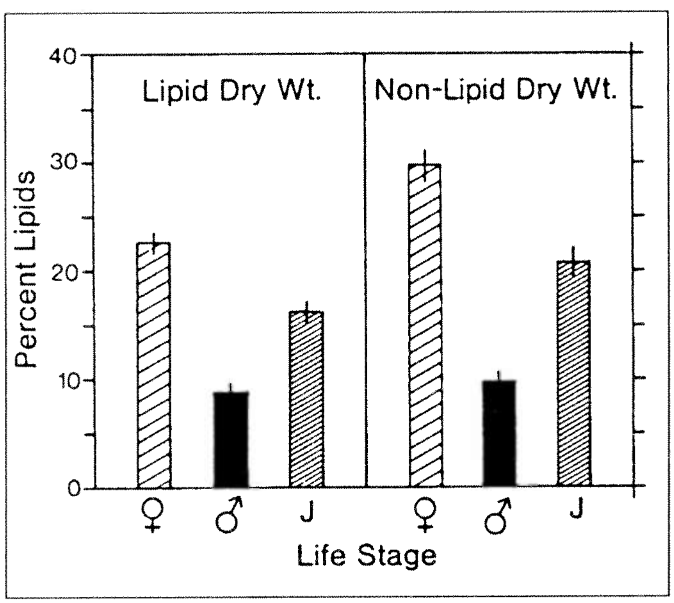


Figure 14. *Mean percent lipid content (SE) of female, male, and juvenile* P. hoyi. *Mean percent lipid content, calculated on a dry weight basis, is shown at left, and mean percent lipid content, calculated on a non-lipid dry weight basis, is shown on the right.*

Mature females had the highest lipid content (23 percent of dry weight) followed by juveniles (16 percent) and mature males (9 percent).

The differences in lipid content among the different life stages means that it is important to account for their relative abundance in a population when trying to estimate the mean lipid content. Most previous estimates have not considered the relative abundance of juveniles vs. adults, and as a result, estimates of mean lipid content may have been highly biased depending on the proportion of life stages.

■ Previous data on *P. hoyi* gut fullnes at a 45-m deep station were compared with similar data obtained by University of Michigan researchers at a 100-m deep station. The results indicate that the profundal populations feed in a more continuous mode than do the near-shore populations. Differences in *P. hoyi* feeding strategies at the two sites may be related to both the quality and quantity of available food.

■ A 1985 (field collection) baseline study of mussel abundances, biomass and composition in Lake St. Clair was completed and documented. This study is the first complete documentation of mussel populations in this lake and provides quantitative data needed to accomplish rate-process studies involving mussels.

Long-term Trends in the Benthic Fauna of the Great Lakes

Responsible Scientist: *T. F. Nalepa*

The composition and abundance of benthic communities have been considered excellent tools for assessing trophic trends in the Great Lakes. Because of their limited mobility and relatively long life cycles (when compared to plankton), benthic fauna form stable communities that integrate and reflect environmental conditions over long periods of time. These changes may be reflected in the presence or absence of sensitive "indicator" species, or, more often, are less dramatic and reflected in subtle shifts in species associations and relative abundances.

Benthic surveys in the mid-1960s clearly demonstrated a degradation of environmental quality when compared to surveys that were conducted some 10 to 30 years earlier; abundances of pollution-tolerant species of oligochaetes increased, while more sensitive species such as the mayfly larvae *Hexagenia* declined. Since the 1960s, a considerable effort has been made to improve the water quality of the Great Lakes. These efforts have focused primarily on decreasing phosphorus inputs into the lakes since this nutrient has been identified as being the most important in causing eutrophication.

GLERL has an established research program to examine trends in benthic populations and to relate these observations to environmental conditions and control measures implemented to improve water quality. This research is consistent with Annex 17, Paragraph (2i) of the 1978 Water Quality Agreement (as amended by protocol in 1987), which delineates the need to determine the impact of water quality on fish and wildlife populations and habitats.

Our approach is to monitor and compare present-day communities to communities of some years past. Sampling programs are designed to duplicate the sampling stations (as closely as possible) and techniques of previously reported studies in order to minimize differences that might be attributed to sampling procedures. Also, sampling is planned to cover several seasons and years to assure that trends are real and not a result of short-term fluctuations. During FY 88 we completed the following work:

- Benthic samples were taken at 30 stations in Saginaw Bay to evaluate long-term trends in benthic populations since the 1950s. Six replicate samples were taken at each of the stations. Sediments were also taken for Dr. Mary Henryof the U.S. Fish and Wildlife Service, National Fisheries Center - Great Lakes, to conduct bioassay studies with *Hexagenia*, and for Dr. Greg Goudy of the Michigan Department of Natural Resources, for contaminant analysis. Analysis of these samples will provide information on how the biota and water quality of Saginaw Bay have changed over the past few decades.

- Benthic samples were collected in Lake Michigan at the same stations sampled in 1980-1981. Since water quality has apparently improved and forage populations have changed since 1980-81, analysis of these samples will determine if benthic populations have changed accordingly.

- Mussel data from western Lake Erie was gathered from two sources (Dr. James Roth, University of California, and Dr. Don Schloesser, U.S. Fish and Wildlife Service, National Fisheries Center - Great Lakes) and a preliminary analysis of long-term trends was completed. This study will bring together three decades of information on mussel abundance and composition.

WATER CIRCULATION, EXCHANGE, AND MIXING DYNAMICS

The movement of water, including circulation, mixing, and exchange of properties, has a major influence upon, and is the direct result of, many ecosystem processes and has direct bearing on many environmental issues. There can be little progress in marine ecosystem assessment without a sound basis for understanding the transport and circulation dynamics of the natural environment. Thus, information about the characteristics of these physical processes is critically important to the development of accurate contaminant fate and ecosystem models.

Lake Michigan Circulation and Dynamics of the Bottom Boundary Layer

Responsible Scientists: ***Dr. J. H. Saylor; G.S. Miller***

The existence of a persistent benthic boundary layer has been documented in the offshore regions of all of the Great Lakes. The layer is identified by a marked decrease in water transparency and may be as thick as 25 m. Although the layer contains, at any point in time, only a small proportion of the total suspended material found in the lakes, sediment trap studies have shown that the bulk of the mass flux occurs within the bottom 25 m.

Any attempt at modeling pollutant pathways must consider resuspension, deposition, and transport within the benthic boundary layer. In particular, it is not known how often, to what extent, or under what conditions, particles may be deposited, eroded, or transported across the lake bottom before becoming permanently incorporated into the sediment. The frequency and magnitudes of resuspension events are of interest because they reinject diagenetically altered material into the lake water.

GLERL has conducted a significant multiyear research effort to measure bottom currents and sediment resuspension in the benthic boundary layer of Lake Michigan. The physics of the bottom boundary layer is being explored with the data sets generated, and the frequency of sediment resuspension in varying water depths and sediment types will be related to the conservative forces driving the lake currents and circulations.

- We completed a study of bottom currents at varying water depths in Lake Michigan off Grand Haven for winter 1987-88. Data collected during the last three winter seasons provide a short climatology of winter-to-winter variations in the lake water temperature, meteorological forcing, and bottom current intensity.

- Analyses of winter current speed measurements reveal long intervals of high velocity bottom flow (>20 cm s-1) which is capable of resuspending the fine-grained sediment observed at the measurement sites. Ekman Layer flow has been observed up to 40 m above the bottom in water depths of 100 m. The Ekman flows are stable over long time intervals during the winter months.

- Persistent cyclonic flow during winter drives upwelling in the center of Lake Michigan's basins. Using the observed Ekman structure in the lake's bottom water, vertical (upwelling) velocities have been computed for the basin centers. Compiled with mixed layer models, the vertical velocities have improved the accuracy with which we can simulate the spring warming of the lake's water mass.

A Three-Dimensional Circulation and Mixing Model for the Great Lakes

Responsible Scientists: ***Dr. D.J. Schwab; Dr. M.J. McCormick***

Numerical models of circulation and mixing are used to better understand and predict the effects of physical processes on the Great Lakes ecosystem. In the past, 2-D circulation models and 1-D mixing models have been developed, tested, and successfully used for simulation and prediction of currents and temperature structure in the Great Lakes. However, many important physical processes can only be studied in a full 3-D context; for example, the effect of Ekman dynamics on vertical advection of heat and development of the seasonal thermocline, the importance of the interaction of the structure of the bottom boundary layer and the horizontal wind-induced circulation pattern for prediction of sedimentation patterns, and the enhancement (or inhibition) of cross-thermocline mixing by internal waves.

For these reasons, GLERL initiated development of a state-of-the-art 3-D circulation model for the Great Lakes. This effort is based on adapting a state-of-the-art 3-D ocean circulation model developed by Mellor and Blumberg (1983). This is a free surface, primitive equation model developed in sigma coordinates to realistically simulate both surface and bottom Ekman layers. The dynamical variables are the three components of the velocity field, temperature, and two quantities which characterize the turbulence: the turbulent kinetic energy and the turbulence macroscale.

During FY 88 we obtained the source code for the Mellor-Blumberg model and implemented it on the Department of Commerce CSCS Cyber 205. It will be appropriately modified for application to the Great Lakes and tested in the following areas:

- Three-dimensional circulation.

- Transport and diffusion of heat and dissolved substances.

- Transport, deposition, and resuspension of suspended material.

Exchange Processes in Coastal Environments

Responsible Scientist: ***Dr. A.W. Bratkovich***

Human populations in most coastal regions are increasing and as a result, increasing demands are being placed on our coastal resources. This trend has exacted a significant toll on the health of coastal water quality and ecosystems as medical wastes, nondegradable plastics, and society's other unwanted "effluents" increasingly foul our waters and close our beaches. The processes that mediate the exchange of physically, biologically or chemically significant fields, especially in our critically important and heavily impacted coastal regions, are poorly understood.

Advective fluxes are a major contributor to the transport of nutrients, contaminants, heat, and other fields of ecological significance. However, accurate estimates of advective fluxes are difficult to make, since detailed characterizations of both the local velocity field and the gradient of the data field of interest are required over a relatively broad range of space and time scales. We must improve basic understanding of the processes contributing to the variability of the velocity field, and to scalar fields such as temperature, in order to better estimate the advective flux of materials in the aquatic environment.

In FY 88, GLERL began research on advective exchange processes in coastal environments with emphasis on the transport of pollutants from their coastal sources to adjacent coastal areas and offshore regions. This research will examine the respective advective roles of various physical processes such as internal waves, fronts, tides, shelf waves, basin modes, riverine inputs, with specific focus on cross-shelf and vertical advective flux components.

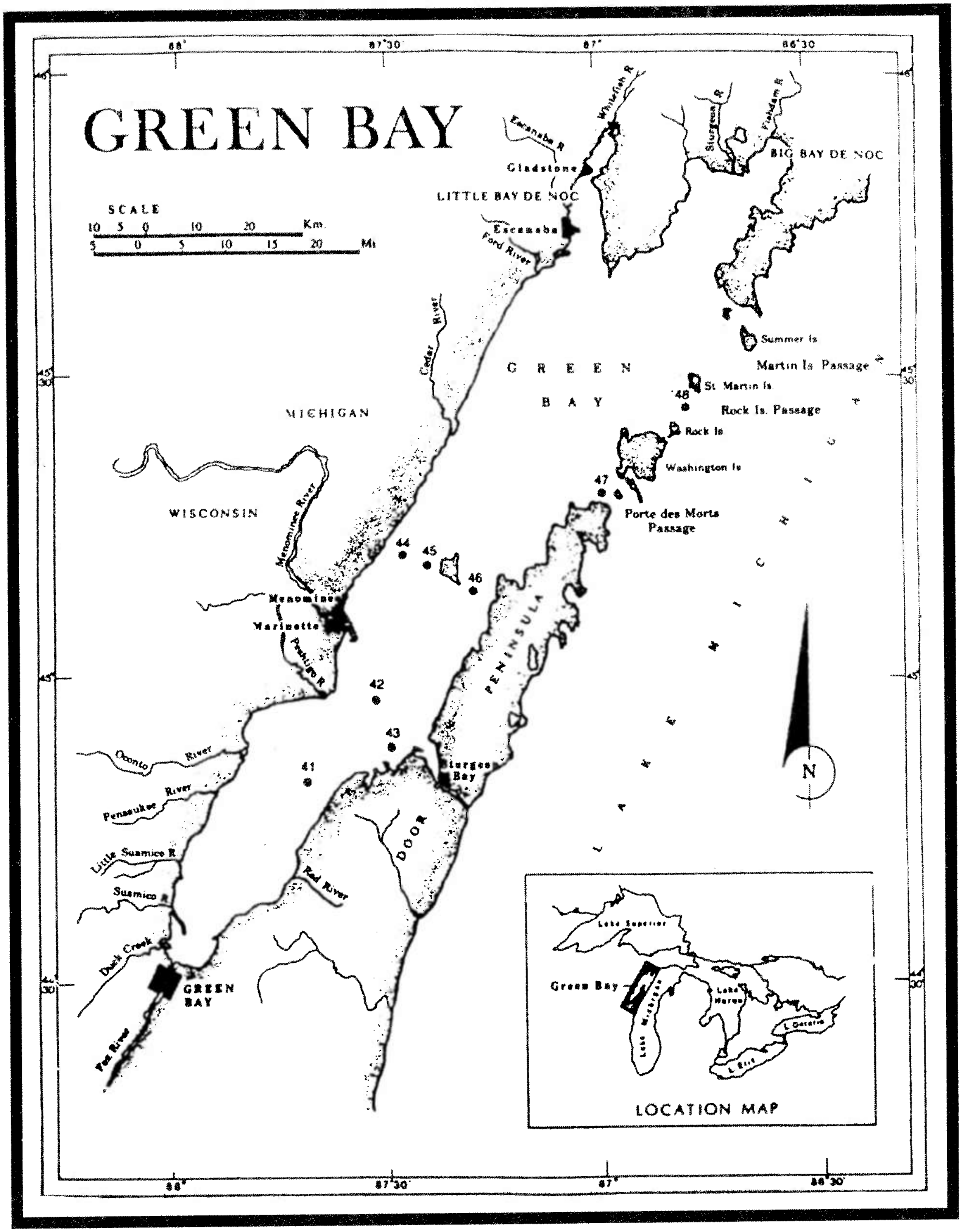


Figure 15. *Winter mooring locations for current meters.*

GREEN BAY MASS BALANCE STUDY

Green Bay is plagued with toxic organics, especially PCBs, in the water, sediment, and biota. The USEPA initiated a major interagency study of Green Bay in FY 88 with the objective of developing as complete and accurate a whole-bay mass balance for PCBs as possible, given funding and technical constraints. A Memorandum of Agreement was established that describes work to be performed by GLERL in support of this study. GLERL has responsibility for three projects, each of which receives partial funding from EPA and the rest from GLERL under the Marine Ecosystems Assessment Program.

Water Volume Transport Measurements in Green Bay

Responsible Scientists: ***Dr. J.H. Saylor; G.S. Miller***

The models necessary to develop a comprehensive Green Bay contaminant mass balance require a knowledge of water volume fluxes throughout the Bay, its tributaries, and to and from Lake Michigan. These fluxes are used to establish boundary conditions for improved hydrodynamic models and for the contaminant mass balance calculations. A previous GLERL study found that the two southern-most passages of the island chain separating Green Bay and Lake Michigan contained the bulk of the volume fluxes between the bay and the lake. The exchange processes are complex; outflow was confined to the upper layers of the water column while inflow of lake water dominated the bottom layers and penetrated deep into the bay. Lake Michigan waters were identified flowing into the lower bay, causing increased flushing.

GLERL will deploy long-term current meter moorings in lower Green Bay to measure water volume transports. Water volume exchanges between the upper and lower parts of Green Bay (at Chambers Island) and between the bay and Lake Michigan will also be measured and will be used for verification of the mass balance and hydrodynamic models. By the end of FY 88, a final plan of study was agreed upon, a quality assurance program was approved, and field deployments of winter moorings were completed (Fig. 15, left page).

Understanding Fish Food Web, Nutrient, and Contaminant Dynamics in Green Bay: An Integrated Modeling Approach

Responsible Scientists: ***Dr. T.D. Fontaine III; Dr. S.W. Hewett (MSU)***

Green Bay is contaminated with PCBs that enter the fish food web through bioaccumulation and direct uptake from water. To understand the relative importance of the various food and water pathways of PCB accumulation by fish, it is necessary to understand food web relationships, population structure, and the bioenergetics of the fish in Green Bay. GLERL will develop a predictive model (Fig. 16) of fish population dynamics and variability in Green Bay as part of its cooperative effort on the EPA Green Bay Mass Balance Study. During FY 1988 an experienced fisheries scientist was hired under contract to install and modify a fisheries model he originally developed for Green Bay.

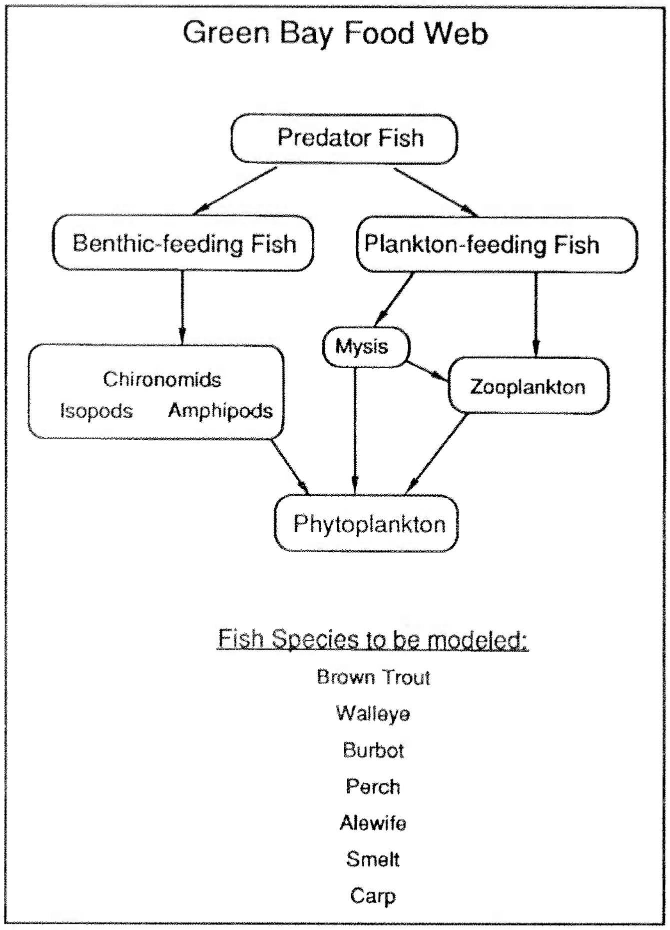


Figure 16. *The basic components of the food web model for Green Bay include the size distribution and abundance of all fish species, and abundances and sizes of the major benthic invertebrates and plankton groups. Concentrations of PCBs in the food chain are partially a function of direct uptake from water and partially a function of accumulation of PCBs through the diet. The species of primary interest in this study are brown trout, walleye, and carp.*

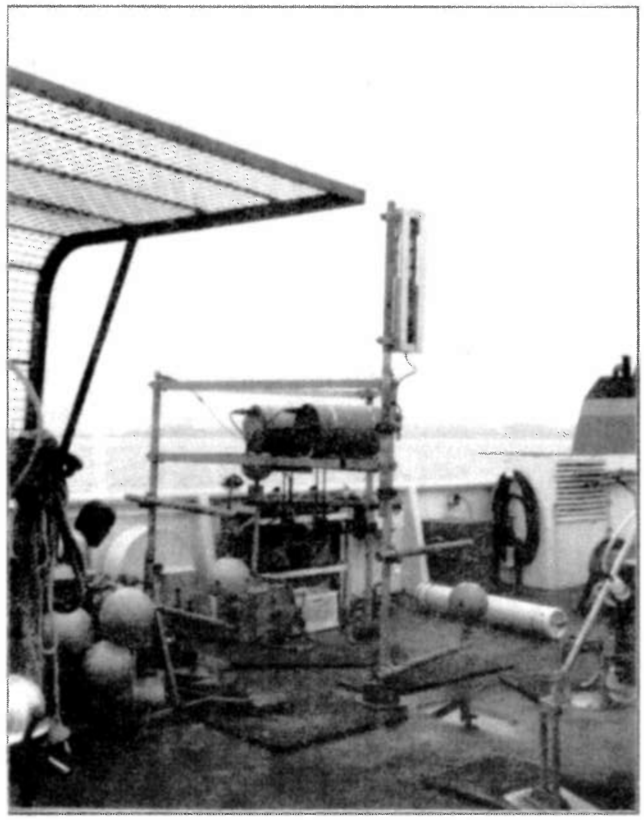


Figure 17. *An instrument tripod for monitoring sediment resuspension. Water transparency is measured by the two transmissometers - one is in the cage on the vertical pipe and the other is suspended below the tripod. Current velocity is measured by the two current meters attached to the tripod legs. The two pressure cases contain the data acquisition system and the power supply.*

Sediment Resuspension in Green Bay

Responsible Scientist: ***Dr. N. Hawley***

Lack of knowledge regarding the processes responsible for the transport and deposition of cohesive sediment remains one of the main difficulties in developing accurate models of pollutant pathways in the Great Lakes. In Green Bay, most of the PCB reservoir is found in sediments, and information about resuspension is needed for the development of a Green Bay mass balance. Two instrument tripods (Fig. 17) were tested in the fall of 1988. Although only one worked, the results show that in shallow parts of the bay (less than 10 m water depth) wave action is a primary cause of sediment resuspension.

UPPER GREAT LAKES CONNECTING CHANNELS STUDY (UGLCCS)

UGLCCS was an international (United States-Canada) and interagency multi-year study of water quality and ecosystem dynamics in the upper Great Lakes connecting channels. Study areas include the St. Marys River, the St. Clair River, Lake St. Clair, and the Detroit River; all are designated by the International Joint Commission as "Areas of Concern" in which environmental quality is degraded and beneficial uses of the water and biota are adversely affected. The goals of the study were (1) to determine the existing environmental condition of the study areas, (2) to identify and quantify the impacts of contaminant loading on ecosystems and human uses of the study areas, (3) to determine the adequacy of existing or proposed programs for ensuring or restoring beneficial uses, and (4) to recommend appropriate programs for protecting the study areas. GLERL was a major participant in the study and FY 88 was the final year of major work on this program, although some related work may be continued into FY 89 under our NOAA base research program because of continued interest and applicability to NOAA's and GLERL's missions.

Ecological Process and Contaminant Fate Models for Lake St. Clair

Responsible Scientist: ***Dr. T.D. Fontaine III***

Lake St. Clair supports a diverse, productive, and economically important fishery. In addition, the lake's relatively good water quality and associated wetlands provide habitats for large numbers of migrating and breeding waterfowl. Recent threats to Lake St. Clair's water quality and biota have come from several fronts. Industrial waste discharges of heavy metals and chlorinated hydrocarbons have impaired the quality of the St. Clair River and other smaller tributaries to Lake St. Clair. Agricultural runoff has caused localized eutrophication problems. Shoreline development has reduced wetlands and increased urban runoff. Winter navigation may also affect environmental quality.

To more fully understand the effects of these factors on fisheries and water quality and to understand the potential benefits of mitigating these factors, GLERL has taken a predictive modeling approach. This type of modeling work is identified as a research need in the 1978 Great Lakes Water Quality Agreement between the United States and Canada, Annex 17, Paragraph (2f), as amended by protocol in 1987, and should aid Great Lakes decision makers in understanding how the Lake St. Clair ecosystem works and the potential effects of their decisions upon it. A series of ecological and contaminant fate models of Lake St. Clair have already been completed and were reported in our FY 86 - FY 87 (Combined) Annual Report. During FY 88:

- Once calibrated and tested using available tracer data, the contaminant fate and transport model for Lake St. Clair was used to simulate and understand polychlorinated biphenyl (PCB) and octachlorostyrene (OCS) dynamics in the lake (Fig. 18).

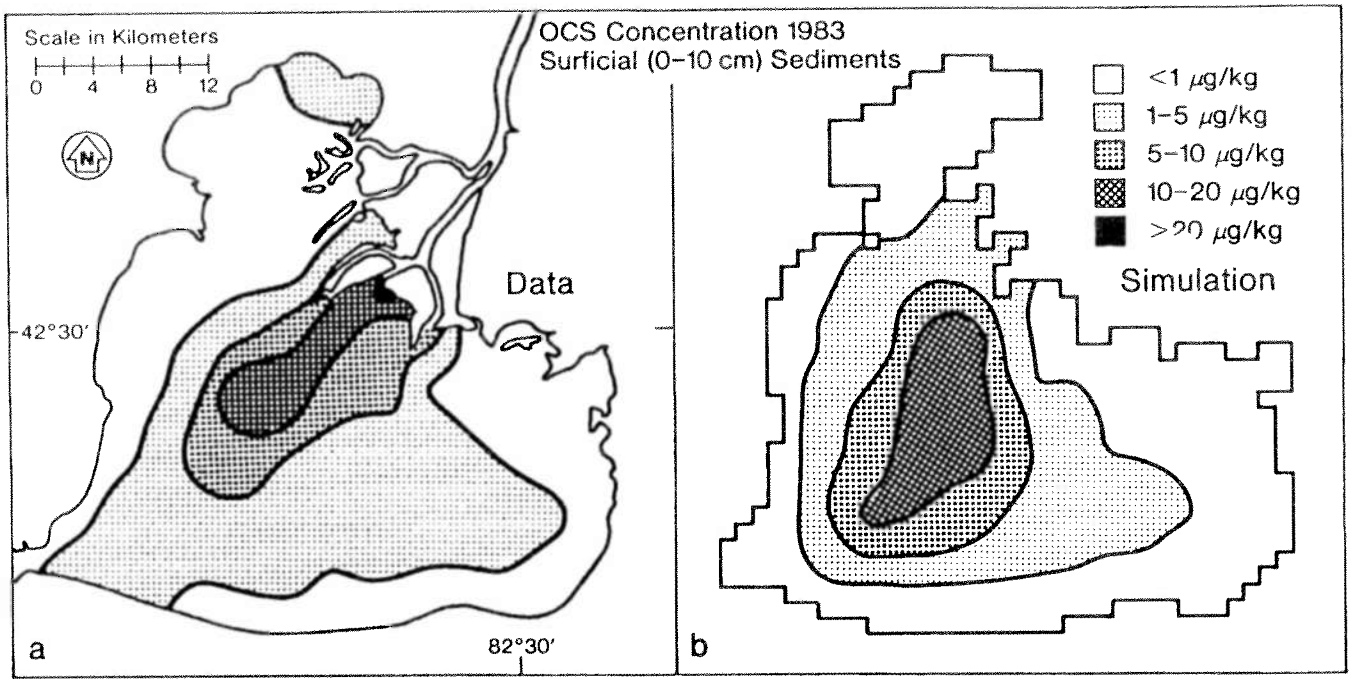


Figure 18. *Comparison of observed (a) and model-simulated (b) concentrations of octachlorostyrene (OCS) in surface (0-10 cm) sediments of Lake St. Clair in 1983. Units in µg kg-1. Model results indicate that from 1971-83, 3.8 MT of OCS entered the system, 2.8 MT were flushed from the lake through the Detroit River, 0.8 MT were lost due to biological degradation and volatilization, and 0.2 MT were deposited in the lake's sediments.*

■ The contaminant fate and transport model for Lake St. Clair was used to predict the extent of cross-boundary (U.S. - Canada) movement of a generic contaminant that would occur under various loading scenarios (Table 2), partition coefficients, and wind directions.

■ A conceptual model and database were completed that will serve as the basis for a predictive model to evaluate the relative importance of various food web pathways to fish production and nutrient cycling in Lake St. Clair.

■ The assumption of chemical equilibrium vs. chemical kinetics as the basis for contaminant-fate models was evaluated by comparing the results for Lake St. Clair from each type of model under certain test conditions.

—The comparison showed that there are circumstances that make it important to consider a kinetics approach, such as when a contaminant is highly partitioned, or when the distribution of contaminants in the input loads cannot be assumed to be in equilibrium.

—Use of the equilibrium-based approach under such conditions could result in erroneous estimates of dissolved, particle-bound, and biologically bound contaminant concentrations as well as errors in the calculated residence times in the system.

Sediment Resuspension in Lake St. Clair

Responsible Scientist: *Dr. N. Hawley*

Lack of knowledge regarding the processes responsible for the transport and deposition of cohesive sediment remains one of the main difficulties in developing accurate models of pollutant pathways in the Great Lakes. To a large extent this is a direct reflection of the difficulty in making accurate quantitative field measurements. It has also not been possible to apply laboratory results to field settings. In order to accurately model the transport processes

Source	Mean System Mass (MT)	Mean Transboundary Movement Mass (MT)	% of System Mass
Can. Sources			
Sydenham R.	3.02	0.17	5.6%
Point 2	2.93	0.21	7.2
Can. St. Clair R.	2.87	0.35	12.2
Thames R.	2.27	0.09	4.0
Point 3	1.45	0.05	3.4
Can. Mean	2.51	0.17	6.9
U.S. Sources			
U.S. St. Clair R.	2.31	1.35	58.4%
Point 1	2.23	0.92	41.3
Clinton R.	1.49	0.65	43.6
Point 4	0.79	0.26	32.9
U.S. Mean	1.70	0.80	46.8

Table 2. *Mean system contaminant mass and transboundary movement at a steady state as a function of load origin for a generic chemical. Transboundary movement is defined as contaminant mass that is transported and ultimately deposited across the U.S. - Canadian border, opposite from its origin. Given equal contaminant loads from various hypothetical sites located around the lake, the model predicted that the Canadian sources would contribute the greatest contaminant mass to the system but the U.S. sources would be responsible for the greatest amount of transboundary movement.*

which affect cohesive materials, long-term synchronous measurements of both sediment concentration and current velocity are required.

In shallow waters the problem is complicated by the presence of wave action. Although waves are not good transporting agents, they are extraordinarily good at resuspending sediment which can then be transported by currents. Thus, the effectiveness of wave action in resuspending bottom material in shallow water needs to be known. This requires monitoring sediment concentration, current velocity, and wave action (or some analog) to develop an empirical relation that predicts bottom resuspension as a function of wave action.

As part of the UGLCCS, three instrumented tripods were deployed in Lake St. Clair for three one-month periods during 1986.

■ Analyses of the records from these deployments showed that a simple mass balance model with a linear forcing term can accurately predict the concentrations at any single station during a given deployment.

—The observations also showed that the measured standard deviation of the current velocity is a good analog of wave orbital velocity and that if on-lake winds are used as input to the GLERL wave model, it produces accurate wave characteristics. However, the estimation of the four parameters required by the model were not consistent between stations during a single deployment or from deployment to deployment at a single station.

—To reduce these differences, during 1988 we modified the model so there is no threshold value of the forcing parameter. This led to greater consistency of the other model parameters (resuspension concentration, ambient concentration, and particle sinking rate) between stations and between deployments. We are now developing the transfer function for calculating overlake winds from shore-based data.

Sediment and Resuspension Processes - UGLCCS Work

Responsible Scientist: *Dr. J. A. Robbins*

The background to this project is described in the Toxic Oragnics And Environmental Contamination Section, pages 6-11. Part of the work done under this project was conducted under the Upper Great Lakes Connecting Channel Study (UGLCCS) program and is reported here.

Contaminants in Lake George Sediments

Sediment cores were collected by a diver from two sites in Lake St. George. This lake, which is situated on the St. Marys River system below Sault St. Marie, receives industrial wastes from major upstream sources.

■ Analyses of ^{137}Cs and ^{210}Pb were completed for all cores. A variable sedimentation-rate model was developed and applied to the measured distributions which were shown to reflect a time-dependent sediment accumulation rate. Based on this information, generic geochronological models can and will be developed for this lake.

■ Neutron activation analyses of these cores for elements such as Fe, Al, Mn, and Zn was also completed, and these data will be used to develop an historical picture of industrial contamination entering the lake.

Particulate Matter Sources in Lake St. Clair

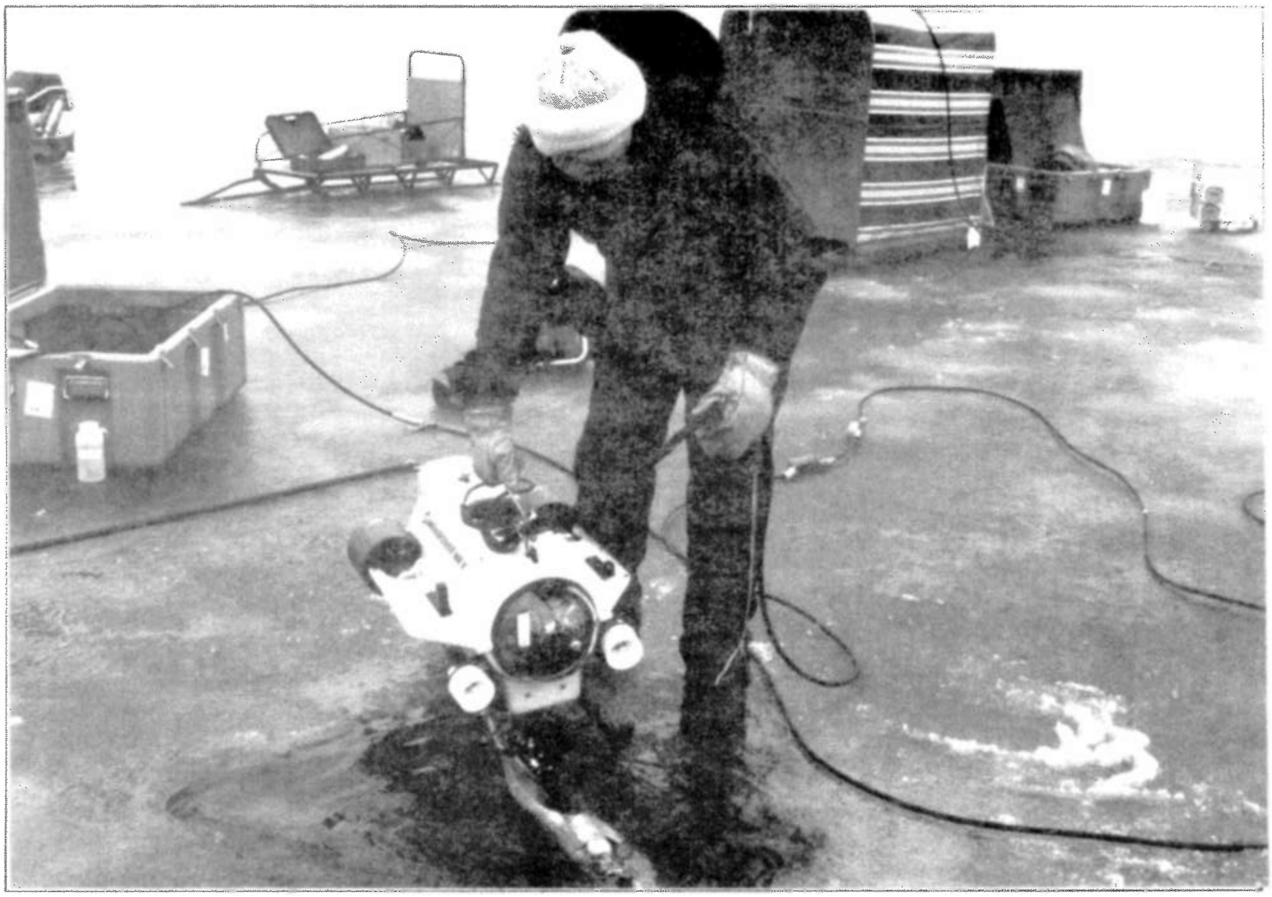
Sediment traps were placed at each of six sites at approximately mid-water column depths for contiguous periods, each of approximately 2 weeks. Traps were retrieved and replaced at the end of each period. Samples from nine 2- week periods between June and November were collected in 1985.

■ Analyses of samples from two sites for ^{137}Cs were completed.

■ Radiocesium exhibits a four-fold variation in concentration at a centrally located site, while data from a more littoral zone shows essentially constant activity.

The contrast between the two sites is probably due to contributions from different particle sources. Fine-grained particles arriving with incoming water from Lake Huron have a radiocesium concentration that exceeds the concentration in resuspended Lake St. Clair sediments by at least an order of magnitude. Thus, the proportion of source material can be determined and can be related to lake circulation and intensity of resuspension. Work is continuing to analyze samples from the other seven sites.

Marine Hazards and Lake Hydrology



Marine Hazards and Lake Hydrology research focuses on (1) improving prediction of environmental phenomena associated with the National Weather Service (NWS) marine warning and forecasting services and the U.S. Army Corps of Engineers (COE) regulation of Great Lakes water flow, and (2) providing better tools and methods for short- and long-term assessments of water resources of large lakes. GLERL research in these areas includes field and analytical investigations to develop simulation and prediction models of overwater wind and wind waves, water surface oscillations, storm surges, and flooding; lake ice formation, growth, movement, and breakup; hydrologic lake levels, water supplies and balance, flows in the connecting channels; and the potential regional impacts of global climate change on the Great Lakes.

MARINE HAZARDS: SURFACE WAVES, WATER-LEVEL FLUCTUATIONS, AND GREAT LAKES ICE

Assessment of Shallow Water Effects on Wind Waves in the Great Lakes

Responsible Scientists: ***Dr. P. Liu; Dr. D.J. Schwab***

Some of the most heavily populated and most intensely utilized areas of the Great Lakes are also the shallowest (Lake St. Clair, Green Bay, Saginaw Bay, and western Lake Erie for example). The nearshore zone is also perhaps the most environmentally sensitive area of the lake, for it is here that major nutrient and contaminant inputs to the lake occur and also where plant and animal activities are concentrated. The effect of waves on these activities needs to be quantified and modeled.

Although wave forecasting methods for deep water are well developed, shallow-water wave forecasting is still in its infancy. GLERL has successfully developed and tested a deep water wave forecast model for the Great Lakes, but has not incorporated any shallow water effects which are known to cause important changes in wave height, wave period, and wave direction in the nearshore zone. A coupled approach of experimental analysis and model development for shallow water wave effects in the Great Lakes is needed.

Using field data, analytical techniques, and numerical models, we are assessing the importance of shallow water effects on wind waves in the Great Lakes by identifying the circumstances and locations in which shallow water effects have a significant impact on wave growth, propagation, or decay and quantifying the extent of that impact. The results will be useful to scientists studying shallow water effects on waves, the coastal engineering community, NWS marine forecasters, and Great Lakes shoreline residents. Our experimental approach is to analyze several existing data sets to quantify shallow water effects on wave propagation. These include:

- Some episodes from the LEX '81 experiment in Lake Erie, where waves measured at a GLERL tower in 14 m of water, were of sufficient amplitude to be affected by the finite depth.

- The data were collected at six towers in Lake St. Clair by GLERL and CCIW during the WAVEDISS '85 experiment which was conducted as part of the UGLCCS program, and major results of which were reported in the UGLCCS Section of the FY 86 - FY 87 (Combined) Annual Report.

- Measurements made in 1986 from the western Lake Erie NDBC buoy (just east of the Bass Islands), the GLERL WRIPS buoy (just west of the islands), and a shallow water tower in Brest Bay will be analyzed to determine how island groups and shallow water affect refraction and shoaling.

- WRIPS buoy measurements from Saginaw Bay in 1987 and Green Bay in 1988 will be examined to separate the effects of shoaling from the effects of narrowing fetch on the wave energy spectrum.

Our theoretical approach in this project focuses on the GLERL/Donelan deep water parametric wave prediction model. It will be tested against shallow water data sets to determine the limitations of its applicability. In the region between the shoreline and where the deep water model becomes applicable, we will compare predictions of several existing theories and models of the behavior of wind waves in shallow water, including the Kitaigorodskii shallow water modification to the JONSWAP spectrum (the so-called TMA spectrum), the empirical techniques suggested by Goda (Goda, Y. 1985: *Random Seas and Design of Maritime Structures*, University of Tokyo Press), and a third generation numerical wave prediction model (WAM). The expected result would be a method for extending the predictions of the deep water wave model in to the shoreline. The implications of shallow water wave modification for resuspension and transport processes in the nearshore zone will also be examined. During FY 1988:

■ GLERL scientists joined the International Wave Model Development Group (WAM Group) to participate in testing the latest state-of-art wave prediction model, the 3rd generation WAM model, on Great Lakes waves. The model was successfully implemented during FY 88 on the Department of Commerce CYBER 205 computer (Fig. 19).

■ Wave measurements from Lake St. Clair obtained under the UGLCCS program were also analyzed for expected and observed directional distributions. Observed directional distributions differ from expected distributions for certain wind conditions that appear to produce bimodal directional spreading functions.

■ A wave measurement buoy was deployed and retrieved in Saginaw Bay. Measurements from the buoy will be used to determine the applicability of numerical wave models to wave prediction for relatively shallow, semi-enclosed areas in the lakes.

Ice Studies

Responsible Scientist: *Dr. S.J. Bolsenga*

Ice in the Great Lakes has a major impact on both the economic and social well-being of the community by

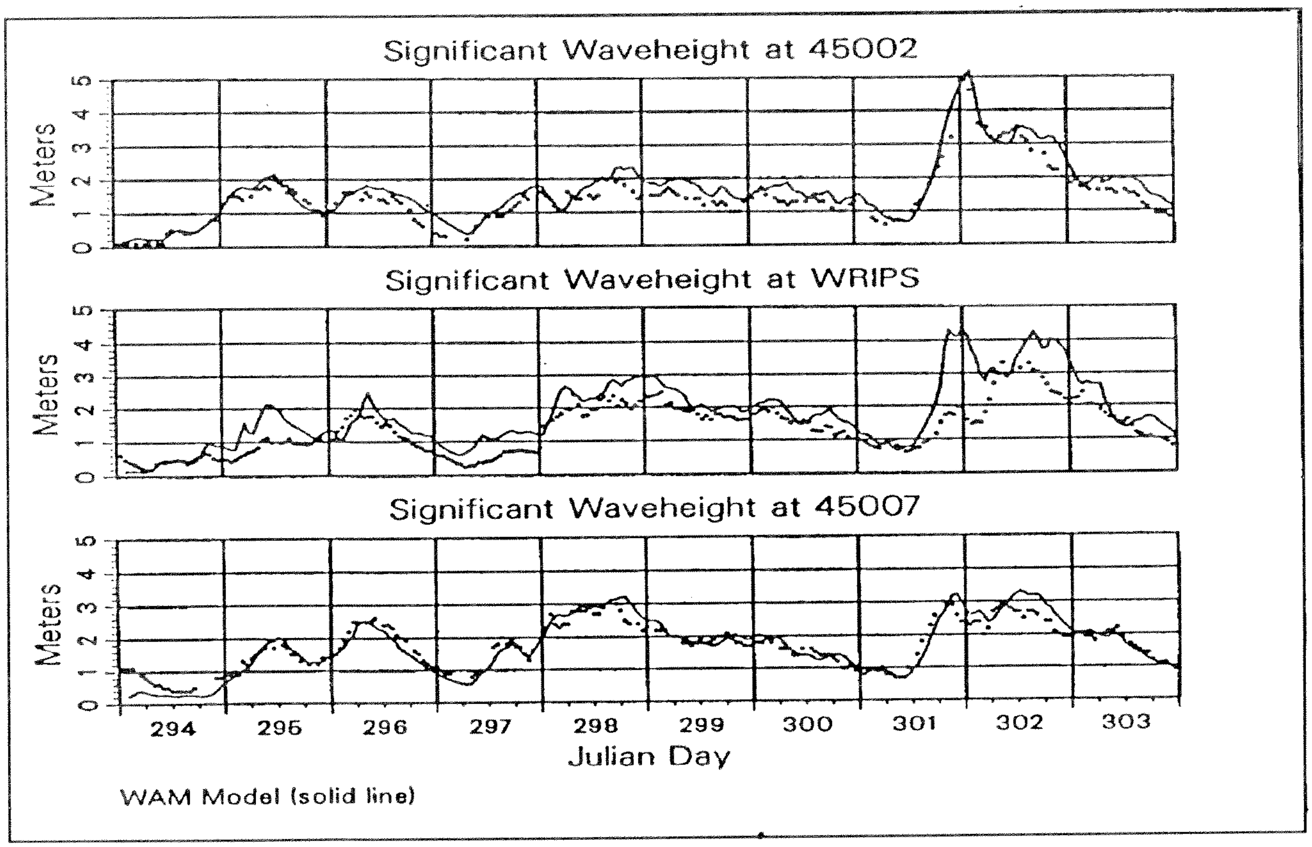


Figure 19. *A comparison of WAM wave model estimated significant wave heights (solid line) with wave measurements (dots) in Lake Michigan.*

affecting winter navigation, flooding, shoreline erosion and damage, hydropower generation, water supplies, fisheries, recreation, and the climate. Understanding, monitoring, simulating, and forecasting the ice cover requires improved information on the formation, growth, movement, and decay of ice; a better definition of the characteristics of ice; and the development of numerical models of the processes governing freeze-up, areal extent, thickness, transport, and breakup of ice.

Due to a shift in emphasis to snow research, efforts in this project are aimed only at completing certain items of previously initiated research.

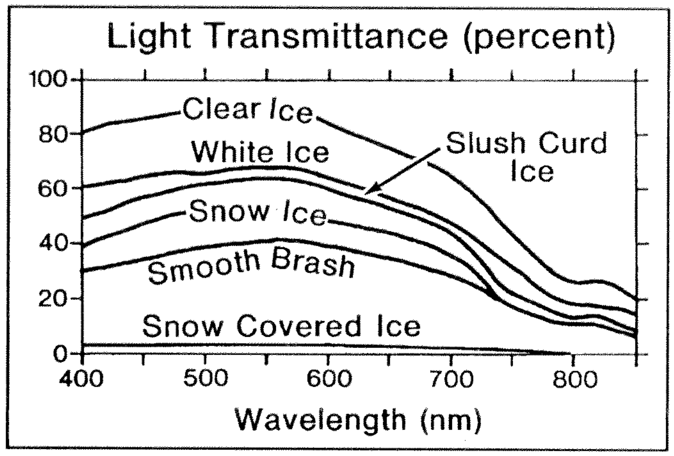


Figure 20. *Spectral transmittances of various types of freshwater ice.*

Spectral Transmittance

This component of the project was initiated during FY 87 to define the spectral transmittance of photosynthetically active radiation (PAR) through various types of common freshwater ice (clear, refrozen slush, pancake ice, etc.) to determine the relationship of through-ice light to under-ice biota.

■ Measurements of the spectral transmittance through various types of freshwater ice have been completed in small wavelength increments over the 400-700 nm range (Fig. 20). During FY 88, these data were analyzed and form the basis of a report to be completed during FY 89.

■ A remotely operated vehicle (ROV) was successfully used to examine the underside of an ice cover on Lake Erie. ROV dives were made under a mixture of clear and refrozen slush ice and near a 3 m-thick ridge. Most of the ice showed smooth undersurfaces with slight visible differences in solar radiation penetration. The vertically oriented crystal structure of columnar ice was easily distinguished by solar radiation transmitted along the partially candled crystal boundaries.

Spectral Reflectance

The spectral reflectance of snow and ice at the earth's surface is affected by sun angle, atmospheric conditions, and surface changes (melting, refreezing, etc.). A detailed understanding of how to correct and interpret spectral reflectance values is required in order to estimate area-wide ice albedo and to use remotely sensed imagery to identify and map ice and snow cover types. During FY 87 a cooperative study was initiated with NASA scientists to document and define the spectral reflectance characteristics in the visible and near-infrared range for various types of ice and snow. A library of such measurements for different ice and snow types could improve interpretation of satellite data from snow and ice covered areas and would help to improve the estimation of hemispheric reflectance, a parameter needed for climate and radiation budget models. During FY 88 we:

■ Used a NASA-built spectroradiometer to collect snow and ice spectral reflectance data in Landsat TM Bands 3, 4, and 5. These data, along with solar-photometer data, shaded and unshaded reference panel data, and sky and target photos were obtained under a variety of sky conditions. Clear-sky diurnal data sets of refrozen slush-covered ice, clear ice, and deteriorated, crusted snow, as well as shaded and unshaded ice and snow were collected. A supplementary data set on the clear-sky specular component of the reflectance was collected using neutral density filters on the radiometer and solarphotometer.

■ Analyses of ice types on Saginaw Bay was initiated using airborne ice reflectance data, corrected using Lambertian factors measured for barium sulfate reference panels, with geometrically corrected AVHRR digital satellite data.

LAKE HYDROLOGY: HYDROLOGIC PROPERTIES

The availability of adequate supplies of fresh water is potentially one of the country's most serious long-range problems. The Great Lakes, with a total combined surface area of 247,000 km^2, contain 23,000 km^3 of water, or approximately 95 percent of the United States fresh surface water. This water is used for navigation, drinking, industrial processes, hydropower, irrigation, transportation, and wildlife and fish habitats. Major changes in water quantity are caused by annual and seasonal variations in the water supply, consumptive use, and interbasin diversions, the latter being anthropogenic changes that have superimposed on the natural fluctuations. GLERL's hydrologic research program is directed toward improving our knowledge of the hydrologic and hydraulic processes, improving methods of forecasting and simulating water supplies and lake levels, and improving large-river dynamic flow models. The research assists in water resource planning and management and in the solution of problems related to water supply, water quantity, shore erosion, flooding, hydropower, navigation, and recreation.

Lake Evaporation Forecasting and Simulation

Responsible Scientist: *Dr. T.E. Croley II*

Evaporation from the Great Lakes is on the same order of magnitude as precipitation and runoff to the lakes. It therefore represents a significant component of the lakes' net supply and its determination is crucial in estimating lake levels. Although lake level forecast accuracy is dependent on meteorological forecasting accuracy, which is poor at present, present evaporation estimation techniques result in the major portion of forecast errors. Lake level forecasts also require better determination of initial basin moisture storages and use of measurements in the forecasts. Water balance determinations of unknown groundwater flows or of net basin supplies cannot proceed until adequate evaporation models are developed; current efforts ignore groundwater and estimate evaporation as a residual.

GLERL has been using evaporation work developed during the International Field Year on the Great Lakes (IFYGL) for Lake Ontario and modified for other lakes; that work uses the aerodynamic equation with mass transfer coefficients developed originally in the Lake Hefner studies of the late 1940s and early 1950s. Unfortunately, there have been no really good independent evaporation data to verify this approach on the Great Lakes. Water balances are insufficient due to the large errors induced by subtracting nearly equal large inflows and outflows to each Great Lake but Superior. Even on Lake Superior, with its relatively smaller inflows and outflows, the water balance allows only a crude comparison.

Since current lake evaporation estimation techniques require knowledge of water surface temperatures, a second problem is that they are not amenable to use in forecast settings since so little is known about the relationship of heat storage in a large lake with evaporation; it is necessary to model both the heat storage and the evaporation process (through consideration of the heat balance and water surface temperature) to enable extrapolation of water surface temperatures for forecasting evaporation. Until recently, when NOAA satellite observations of water surface temperatures became widely available, such consideration was not possible.

This research will lead to working models of lake evaporation that can be used effectively on daily, weekly, and monthly time intervals for each of the Great Lakes. These models will be incorporated into the GLERL water supply and lake level simulation and forecasting procedures. During FY 1988:

■ A superposition heat storage model appropriate for deep lakes, where surface temperature increases associated with heat increments are superimposed, was derived from basic considerations of the lumped thermal structure in deep lakes.

■ Recent mass-transfer-coefficient research was combined with lumped model concepts of classical energy conservation, surface heat fluxes, and superposition heat storage to provide the capability for continuous simulation of both water surface temperatures and lake evaporation for use in outlooks and forecasts of lake levels.

■ The resulting lake evaporation model was calibrated for Lakes Superior, Huron, St. Clair, Erie, and Ontario against daily surface temperature data derived from NOAA satellite coverage (Table 3); it was applied to determine surface temperatures, evaporation, and heat budgets historically (1948-85) and over the average annual cycle for these lakes. These products compared favorably to other measurements of heat fluxes and other evaporation estimates in water balances.

■ Lake-averaged ice concentrations were calculated from simulated basin mean ice concentrations for Lakes Erie and Superior for the winters of 1897-98 to 1984-85. These data will be used in lake evaporation models to evaluate the utility of improved ice cover data in modeling lake evaporation.

■ The lake evaporation models for all lakes but Michigan were applied to establish an interim model for Michigan and were incorporated in the integrated models for determining lake levels throughout the Great Lakes.

Lake Level Management

Responsible Scientist: *Dr. Frank H. Quinn*

On August 1, 1986, the Governments of the United States and Canada, pursuant to Article IX of the Boundary Waters Treaty of 1909, forwarded a Water Levels Reference to the International Joint Commission. The Reference requested that the Commission examine and report upon methods of alleviating the adverse consequences of fluctuating water levels in the Great Lakes-St. Lawrence River Basin.

GLERL scientists provide hydrological and climatological analyses, simulation and forecasting techniques, and technical expertise to the functional groups of the IJC, in support of the Reference. During FY 88:

■ Climate scenarios representing two wet and two dry 12 year sequences were developed based upon the long-term GLERL precipitation data base. Meteorological parameters for the scenarios were input to GLERL's large basin runoff and evaporation models, and net basin water supplies were simulated for each scenario. Lake level simulations using the GLERL routing model indicated a relatively small increase in lake levels for the wet scenario and a relatively large decrease in lake levels for the dry scenario, as compared with recorded water levels adjusted for present diversions and channel regimes.

■ A database of monthly Great Lakes precipitation and air temperature was developed for each lake basin for the period 1859-1899.

■ A detailed review was conducted of government expenditure, tax, and information programs that have potential to reduce damages caused by fluctuating Great Lakes levels. The review was based on an extensive literature review, interviews with agency and representatives from various Great Lakes interests, and a workshop comprised of Great Lakes and coastal hazard experts. The findings were submitted to the IJC Project Management Team of the Reference.

Daily lake evaporation model calibration results, FY88.

	Lake				
	Superior	Huron	St. Clair	Erie	Ontario
Surface Area, km^2	82100	59600	1114	25700	18960
Volume, km^3	12100	3540	3.3	484	1640
Average Depth, m	147	59.4	3.05	18.8	86.5
CALIBRATION PERIOD STATISTICS (1979-85)[a]					
Number of Observations	110	165	64	150	189
Means Ratio[b]	1.05	0.99	1.09	1.03	0.98
Variances Ratio[c]	0.95	0.97	1.34	1.16	0.98
Correlation[d]	0.98	0.98	0.97	0.98	0.98
R. M. S. E.[e]	1.20	1.32	2.81	1.95	1.48
VERIFICATION PERIOD STATISTICS (1966-78)					
Number of Observations	94	160		104	149
Means Ratio[b]	0.95	0.98		1.12	1.05
Variances Ratio[c]	1.11	0.99		1.42	1.02
Correlation[d]	0.93	0.98		0.97	0.98
R. M. S. E.[e]	1.62	1.26		2.76	1.57
COMBINED PERIOD STATISTICS (1966-85)					
Number of Observations	204	325	64	254	338
Means Ratio[b]	1.00	0.99	1.09	1.07	1.01
Variances Ratio[c]	1.00	0.97	1.34	1.25	0.99
Correlation[d]	0.96	0.98	0.97	0.97	0.98
R. M. S. E.[e]	1.41	1.29	2.81	2.31	1.52

[a]Data between 1 January 1979 and 31 December 1985 for all Great Lakes and between 1 January 1979 and 31 December 1983 for Lake St. Clair.
[b]Ratio of mean model surface temperature to data mean.
[c]Ratio of variance of model surface temperature to data variance.
[d]Correlation between model and data surface temperatures.
[e]Root-mean-square error between model and data surface temperatures in degrees Celsius.

Table 3. *Remotely-sensed surface temperatures from NOAA's Polar Orbiting Satellites AVHRR and from Canada's Atmospheric Environment Service airborne surveys of water surface temperature were used to calibrate GLERL's lake evaporation model. This table shows summary statistics from the calibrations comparing the actual data with the models. The goodness-of-fit statistics for calibration and verification periods show generally good fits between the actual and calibrated-model surface temperatures for the deep lakes; correlations are high and means and variances are close between the data and the model for each lake.*

Detroit River Unsteady Flow Analysis

Responsible Scientist: *J.A. Derecki*

The Detroit River is a funnel conveying the water from the upper Great Lakes to Lake Erie and serves as the dilution source for many industrial and municipal waste discharges. The flow can vary rapidly in response to storm surges and wind setups on Lake Erie, even reversing (flowing north) at times. These flow reversals disrupt the normal contaminant pathway and could transport contaminants back into Lake St. Clair that would ordinarily flow into Lake Erie.

GLERL has been operating an acoustic Doppler current profiler in the Fort Wayne section of the river to record flow variations with time, especially those that occur during wind setups and storm surges on Lake Erie. The results of this project are expected to provide a better understanding of unsteady flow conditions in the river, including flow reversals, and to improve the calibration of existing Detroit River unsteady flow models.

■ During 1988 a comparison of the vertical velocity profiles obtained with an Acoustic Doppler Current Profiler (ADCP) was completed and the data were used to verify a theoretically developed vertical velocity distribution for the connecting channels.

■ On December 15, 1987, the first actual measurement of a flow reversal in the Detroit River was recorded by the ADCP (Fig. 21). Analysis revealed that hourly instantaneous water levels, which represent the shortest period for which data are normally available, are too far apart for the flow reversal simulation. Hourly models grossly underestimated or completely missed the flow reversal. This, and exclusion of the wind shear in previous Detroit River flow reversal studies, casts doubt on the results of such previous studies.

■ The existing Detroit River unsteady flow models (Upper, Island, and Total river model versions) were modified to operate with the 15- and 5-minute water level inputs for the analysis of flow reversal. Inclu-

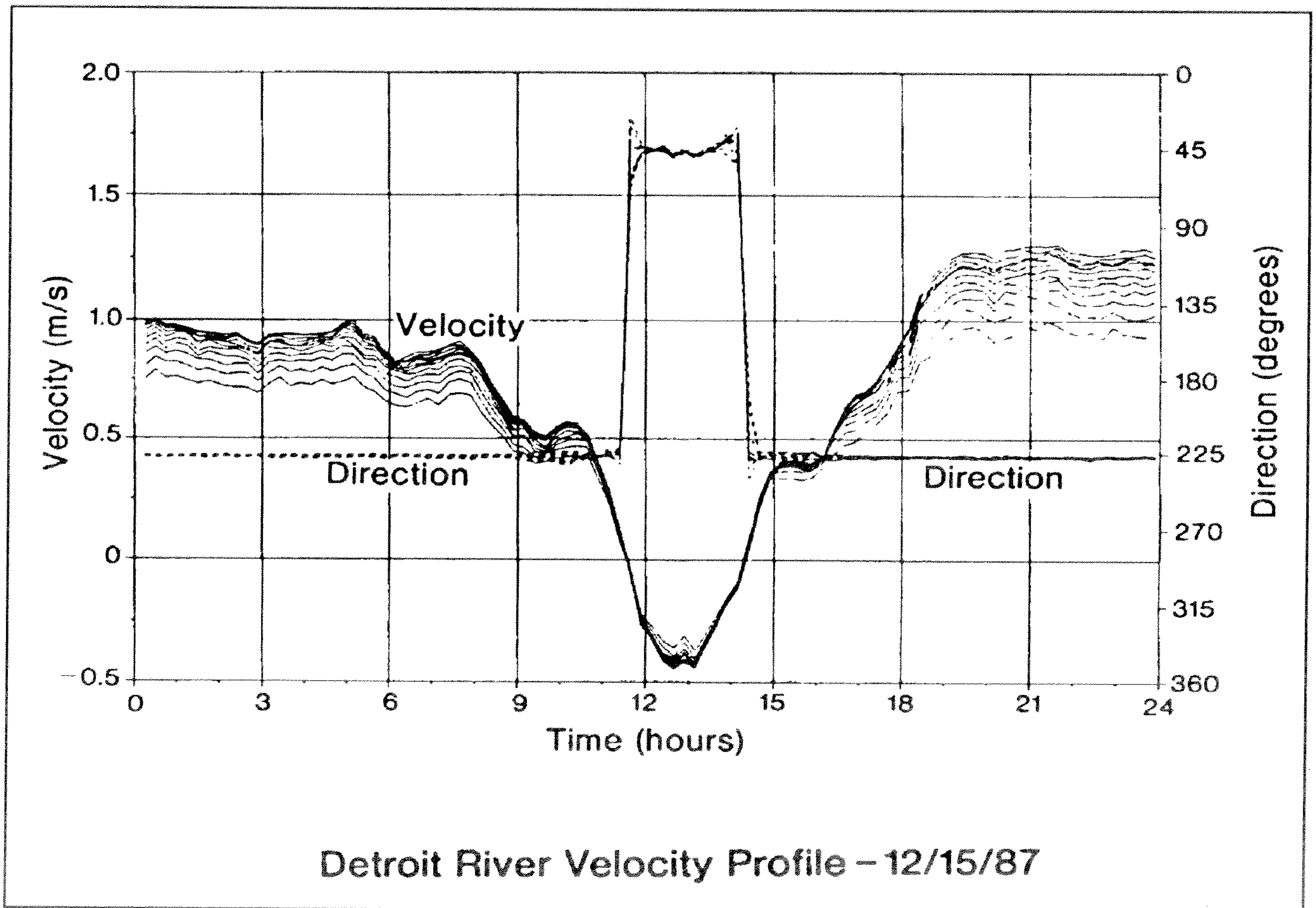


Figure 21. *Velocity measurements with the ADCP meter indicate vertical velocity distribution of water velocity and direction for 11 successive depth levels, and clearly show that the flow reversal process affected the entire water column from the surface to the bottom.*

sion of surface wind shear and the shorter time-steps produced large computation improvements but failed to duplicate measured results (Fig. 22). Thus, the problems with the existing models cannot be solved by simple model recalibration.

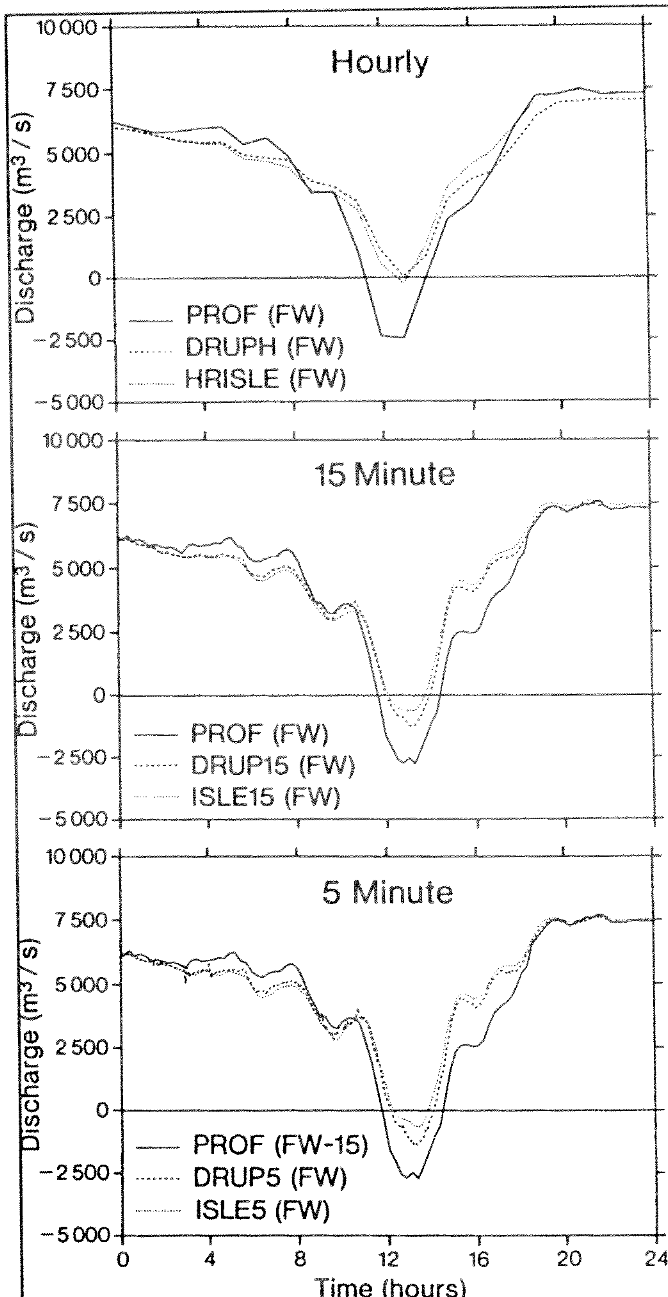
Great Lakes Snow Cover

Responsible Scientist: *Dr. S.J. Bolsenga*

Snow cover represents a vast reservoir of freshwater that, during the spring, contributes to the water supply of the lakes and to the groundwater of the basin, thus influencing hydroelectric power generation, commercial navigation, lakefront property owners, and recreational boaters. The climatology of the Great Lakes snow cover is largely unknown. Atmospheric circulation affects air mass movement over the Great Lakes, and studies relating northern hemisphere atmospheric circulation and seasonal snowfall are needed to increase our understanding of the causes of annual variations in snowfall and snow cover. In addition, the processes of air mass modification by the lakes during winter is poorly understood. As air masses move over the lakes, they acquire or discharge moisture depending on their direction of movement, initial characteristics, the amount of ice/water present on the lakes, and the physical characteristics of landmasses. Improved understanding of these processes will lead to better mapping and prediction of snow cover which will, in turn, aid the various user interests mentioned above.

Under this project we will develop monthly, yearly, and period-of-record snow cover maps for the Great Lakes basin, develop improvements to the methods available to map the Great Lakes basin snow cover, focusing on applications of remote sensing technology, and we will examine the relationship between northern hemisphere atmospheric circulation and Great Lakes snowfall and snow cover.

- Extensive program planning was accomplished during FY 88 and the technical plan was completed. Work began on building databases of snow-on-the-ground and snowfall for the entire basin. An extensive amount of data has been acquired from other agencies in the U.S. and Canada. These data will be organized for processing by mapping techniques.



PROFILER VS. MODEL DISCHARGES
MEASURED VS. SIMULATED WATER FLOWS
DECEMBER 15, 1987

Figure 22. *Comparison of measured (PROF) and model-simulated flow reversals shows marked improvement for shorter computational time steps (hourly, 15 minutes, and 5 minutes), but indicates that flow differences between measured and simulated values are still considerable, despite the inclusion of surface wind shear.*

LAKE HYDROLOGY: REGIONAL IMPACT OF CLIMATE CHANGE IN THE GREAT LAKES

Climate change, represented by global warming or cooling, can significantly affect the global environment and has thus received the attention of world leaders and the world scientific community. However, from a socioeconomic and human standpoint, it is the regional effects that will be of direct concern to the majority of environmental resource managers and local governments. Due to the large and slowly changing storages of water and heat in large lakes, they buffer the effects of most short-term (interannual) meteorologic variability and react to, and record, the longer period fluctuations characteristic of global climate change. Thus, large lakes may be ideally suited for studying the regional effects of global climate change. As a start, GLERL has established a core research program to examine and evaluate the potential effects of climate change on the Laurentian Great Lakes.

Impact of Climate Change on Great Lakes Water Levels, Ice Cycles, and Thermal Regime

Responsible Scientist: ***Dr. T.E. Croley II***

The Great Lakes system is one of the most intensively used fresh water systems in the world, serving multiple interests including navigation, hydropower, recreation, and riparian. Great Lakes ice cover affects winter temperature and precipitation patterns. It also has a major impact on the economy of the region by impeding and eventually stopping commercial navigation, interfering with hydropower production and cooling water intakes, and damaging snow structures. Global warming or cooling could significantly change Great Lakes water levels and ice covers and their related interests. GLERL's research is focused on assessments of (1) the effects of global warming [as represented by a doubling of atmospheric carbon dioxide (CO_2)] on Great Lakes water supplies, lake levels, and ice cover, and (2) the potential effects of precipitation as great as those recorded for the period 1870-1885, but for present basin characteristics, diversions, regulations, and connecting channel regimes.

■ Models of rainfall and runoff, overlake precipitation, and heat storage and lake evaporation were combined with operational regulation plans and models of outlet and connecting channel flows to estimate Great Lakes water levels. The integrated models were linked to atmospheric changes derived from general circulation models (GCMs) for a doubling of atmospheric CO_2. Simulations were made for all Great Lakes for three different steady-state GCMs and a base case (Table 4), and for a transient GCM and base case.

—Net basin supply time series simulated for each GCM and the base case were supplied to the U.S. Army Corps of Engineers, Canada Centre for Inland Waters, and the Great Lakes St. Lawrence Study

Average Annual Steady-State Great Lakes Basin Hydrology and Net Basin Supply Components for $2xCO_2$ simulations.

Scenario	Over Land Precipitation (cms)		Evapotranspiration (cms)		Basin Runoff (cms)		Over Lake Precipitation (cms)		Over Lake Evaporation (cms)		Net Basin Supply (cms)	
BASE	13637		7727		6090		6499		5352		7237	
GISS	13871	+2%	9317	21%	4658	-24%	6747	+4%	6821	+27%	4584	-37%
GFDL	13725	+1%	9176	19%	4714	-23%	6501	+0%	7685	+44%	3530	-51%
OSU	14483	+6%	9204	19%	5438	-11%	6903	+6%	6745	+26%	5596	-23%

Table 4. *This table summarizes average annual steady-state flowrates in cubic meters per second (cms) for the entire Great Lakes basin for the base case ($1xCO_2$) and each of the $2xCO_2$ general circulation model simulations available from Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU). While precipitation over the land and lake change little for the entire Great Lakes basin, evaporation and evapotranspiration increase resulting in lowered runoff to the lakes and greatly lowered net basin supplies to the lakes.*

Office. They will be used in the IJC Great Lakes Water Levels Reference Study to determine what levels may be expected in the long-term.

—In general, the $2xCO_2$ scenarios led to higher evapotranspiration and lower runoff to the lakes, earlier runoff peaks, and great reductions in snowpack and soil moisture.

—Modeled water surface temperatures peaked earlier on Lake Superior, and larger amounts of heat became resident in the deep lakes throughout the year. Buoyancy-driven turnovers did not occur in the deep lakes, ice formation was greatly reduced, and lake evaporation increased over all lakes.

—Average steady-state lake levels dropped between 0.5 m and 2.5 m depending on the lake and the scenario studied.

—Transient analyses of an 80-year warming to the $2xCO_2$ condition indicate the lake levels could drop 13-93 mm per decade. In addition, the Lake Ontario regulation plan failed in all analyses, reflecting the inadequacy of its design based on current ranges of levels and flows and the need to reconsider existing regulation plans for the long-term.

■ GLERL acquired the U.S. Historical Climatologic Network data set, which comsists of two centuries of meteorologic data obtained at many stations. These data will be extremely valuable for studying recent climate changes.

■ Freezing degree-day ice concentration models were developed for Lakes Erie and Superior. Models were applied to a 1951-80 base period (Fig. 23), to three $2xCO_2$ warming scenarios, and to a transient CO_2 warming scenario (1981-2059). This study provides new information on the potential sensitivity of Great Lakes ice cycle to global warming.

Results for the $2xCO_2$ scenarios (Table 5):

—Average ice cover duration was 5 to 13 weeks shorter than the base period ice cover duration (13 to 16 weeks).

—Winters without ice cover became common for the center and east basins of Lake Erie.

—Ice cover was limited to shallow areas and lake shorelines during most winters.

Results for the transient scenario:

—The ice cycle did not change significantly during the first 30 years (1981-2009) of the transient scenario, but during the 30 year period that followed (2010-

2039), ice concentration was significantly less and ice duration was 3 to 7 weeks shorter.

—During the last decade of the transient scenario (2050-2059), ice concentration and duration approached the $2xCO_2$ scenario conditions.

■ The effects of climatic warming on the thermal structure in southern Lake Michigan included higher surface temperatures and heat content, a deeper mixed layer during early winter, a shallower mixed layer during summer with less energy available for mixing, an earlier onset of density stratification, and a significantly longer stratified season, and the possibility in deeper areas of a permanent thermocline.

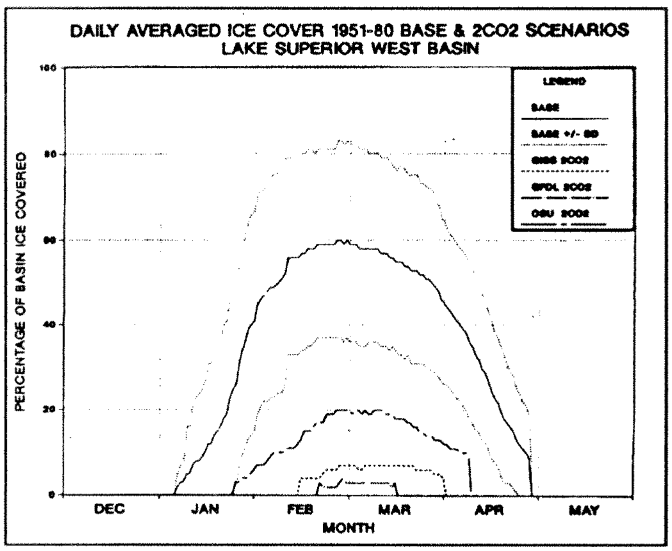


Figure 23. *Daily averaged ice concentration for Lake Superior's west basin for the 1951-80 base period and the three 2xCO2 scenarios. The solid line is the 1951-80 average, the dotted line is the standard deviation, which represents the variability of ice cover for the base period. Sixty percent of the basin is ice covered for the period while only 20 percent or less of the basin is ice covered for the various 2xCO2 scenarios, implying that only shore ice will form during an average 2xCO2 winter.*

PERCENTAGE OF WINTERS WITHOUT ICE COVER

Scenarios		Lake Superior WB	Lake Superior EB	Lake Superior WFB	Lake Erie WB	Lake Erie CB	Lake Erie EB
Base	1951-80	0	0	0	0	3	3
2xCO2	GISS	0	0	0	10	67	80
2xCO2	GFDL	0	7	7	17	73	83
2xCO2	OSU	0	0	0	7	37	60

2xCO2 - double CO2 global warming scenario
GISS - Goddard Institute of Space Science
GFDL - Geophysical Fluid Dynamics Laboratory (ERL)
OSU - Oregon State University
WB - west basin
EB - east basin
WFB - Whitefish Bay
CB - center basin

Table 5. *Percentage of winters without ice cover for the 1951-1980 base period and the three 2xCO2 scenarios. Note that only 3 percent of the winters for the center (CB) and east (EB) Lake Erie basins had winters without ice cover during the base period. During the 2xCO2 scenarios 37 percent to 83 percent of the winters for these same two basins were without ice formation.*

Outreach Activities

In FY 88, GLERL took an active lead to better inform the public about Great Lakes research efforts being conducted by NOAA/ERL/GLERL by sponsoring its first Open House. Participation by other Great Lakes research agencies as well as a strong show of interest and support by the community made this a positive and worthwhile event.

The GLERL mission includes the development of environmental information, data, and service tools in support of user needs in government and private organizations. Identifying the environmental information needed to fulfill GLERL's mission helps guide our research programs and is a vital activity of GLERL staff. Participation on boards, commissions, task forces, and committees is an essential part of this effort. An equally important role is played by the Publications Unit (see Facilities and Services, page 53), which supports all aspects of publishing GLERL's products, making GLERL publications available to those who need them, as well as answering information requests, and creating displays and general literature concerning GLERL's products and work.

International and Interagency Participation

Staff participation on boards, commissions, task forces, and committees provides a mechanism for defining new research initiatives, identifying user needs, and guiding the development of usable products. It helps to maintain staff involvement in programs concerned with environmental problems and keeps staff familiar with water- and land-oriented resource development and management issues.

During FY 88 GLERL staff participated as members of the following International Joint Commission boards, committees, and task forces:

- Corporate Management Committee (A. Beeton)

- International Great Lakes Technical Information Network Board (F. Quinn)
  - Hydrology Committee (T. Croley)
  - Systems Evaluation Committee (T. Croley)

- International Great Lakes Levels and Flows Advisory Board (F. Quinn, U.S. Co-chair)

- Great Lakes Water Quality Board, Surveillance Work Group
  - Great Lakes Surveillance Work Group (P. Landrum)
  - Lake Michigan Task Force (B. Eadie)
  - Lake Erie Task Force (J. Robbins, Consultant)
  - Lake Huron Task Force (T. Nalepa)
  - Surveillance Design in Areas of Concern (D. Scavia)
  - Task Force on In-Place Sediment Contaminants, Workshop on Monitoring in Areas of Concern (B. Eadie, Co-chair)
  - Upper Connecting Channels Task Force (J. Derecki)
  - Workshop on Atmospheric Input to the Great Lakes (B. Eadie)

- Great Lakes Science Advisory Board (A. Beeton, U.S. Chair)
  - Council of Great Lakes Research Managers (D. Reid)
  - Great Lakes Levels Task Force (F. Quinn, Chair)

Other interagency, professional society, and international activities:

- American Geophysical Union
  - Committee on Personal Computers (T. Croley)

- American Institute of Hydrology
  - Michigan Section (T. Croley, President)

- American Meteorology Society
  - Hydrology Committee (F. Quinn)

- American Society for Limnology and Oceanography
  - Board of Directors (D. Scavia)

- Coordinating Committee for Great Lakes Basic Hydraulics and Hydrologic Data
  - Riverflow Subcommittee (F. Quinn)

- Department of Commerce Consolidated Scientific Computing System Technical Committee (G. Spalding)

- Green Bay Study Mass Balance Study (USEPA)
  - Field Operations Committee (N. Hawley)
  - Management Committee (A. Beeton)
  - Modeling Work Group (T. Fontaine, J. Saylor)
  - Technical Advisory Committee (B. Eadie, P. Landrum)
  - Lake Ontario Division (John Robbins)

- Huron River Watershed Council (D. Scavia, S. Tarapchak, Advisors)

- International Association for Great Lakes Research
  - Board of Directors (F. Quinn, Past-President, Secretary; D. Schwab, Treasurer; B. Eadie, Vice-President)
  - IAGLR Membership and Endowment Committee (M. Quigley, Chair; T. Nalepa, V. Chair)
  - *Journal of Great Lakes Research* (F. Quinn, Associate Editor)

- International Association for Hydrologic Research
  - Section on Water Resources Systems (T. Croley, U.S. Representative)

- International Association on Water Pollution Research and Control Specialist Technical

IJC Great Lakes Levels Reference
FWR Functional Group 2 Hydrology + Climate Hydraulics
Wells 3 SFET

Group on Systems Analysis in Water Quality Management (T. Fontaine)

- International Association of Theoretical and Applied Limnology
  (A. Beeton, U.S. Representative)

- Lake Ontario Dioxin Superfund Expert Panel (USEPA) (B. Eadie)

- NOAA Technical Subcommittee, New Bedford Superfund Action (B. Eadie)

- State of Michigan, Department of Natural Resources
  Great Lakes Information System Technical Advisory Committee
  (A. Beeton)
  Hazardous Waste Assessment Committee
  (B. Eadie, P. Landrum)
  Toxic Substances Control Commission
  (A. Beeton, Commissioner)

- University Council on Water Resources
  (T. Croley)

- University of Michigan
  Biological Station Executive Committee
  (A. Beeton)
  Ph.D Committee (B. Eadie)

- Sea Grant Research Advisory Committee
  (J. Saylor, A. Bratkovich, A. Beeton)

- Upper Great Lakes Connecting Channel Study (UGLCCS)
  Biota Work Group (T. Nalepa)
  Management Committee (A. Beeton)

- U.S.-Canada Ice Information Working Group (~~F. Quinn~~, U.S. Co-Chair; R. Assel) R

- U.S. Soil Conservation Service
  (A. Beeton, Technical Advisor)

GLERL scientists also:

- conducted cooperative research and exchange visits with scientists from NASA/Goddard Space Flight Center (G. Leshkevich);
- Contributed to the development an Estuarine Research plan with other NOAA components (B. Eadie);
- Served on six doctoral committees at The University of Michigan;
- Served as adjunct professors at The University of Michigan;
- Conducted cooperative research with the U.S. Geological Survey on the geochemistry of the Oahe Reservoir System, S. Dakota;
- Conducted cooperative research with the U.S. State Department on Chernobyl Fallout in Masurian Lakes, Poland;
- Conducted cooperative research with scientists from the University of Konstanz, W. Germany on a comprehensive study of Chernobyl Fallout in Lake Konstanz;
- And conducted cooperative research and exchange visits with scientists from Argonne National Laboratory, Pacific Marine Environmental Research Laboratory, University of Michigan, Canada Centre for Inland Waters, Ministry of the Environment (Canada), University of Minnisota, Case Western Reserve University, U.S. Geological Survey inUrbana, IL, Bowling Green State University, Skidaway Institute of Oceanography, and the U.S. Fish and Wildlife Service, National Fisheries Center - Great Lakes.

Meetings and Presentations

An integral part of the scientific development of GLERL staff is attendance and participation in scientific and technical meetings. During FY 88, GLERL sponsored over 28 in-house seminars as part of the GLERL Informal Seminar Series, and 165 presentations concerning GLERL's work were made by our staff at public and professional meetings. In FY 88, a GLERL staff member served as a Session Chairman at the Third International Conference on Ecology and Environmental Quality, Jerusalem, Israel.

Cooperative Study GLERL USSR Scientists on Evaporation and climate Change

Technology Transfers

GLERL staff responded to approximately 1,200 requests for information during FY 88, and provided over 2,700 items to service those requests. Among the products that GLERL produces and distributes, many involve, to some degree, a transfer of technology as well as data. During FY 88, GLERL's outreach of this nature involved the transfer of computer-based software providing improved techniques for natural hazard preparedness.

Storm Surge Planning Software

Copies of this GLERL-developed software and advice on its proper application and limitations were provided to the following organizations:

- U.S. Army Corps of Engineers
- Ohio Department of Natural Resources
- Wisconsin Department of Natural Resources
- Michigan Department of Natural Resources
- Wisconsin Sea Grant
- Toledo Edison Electric Co.
- Atmospheric Environment Service of Canada
- National Weather Service Forecast Office (NWSFO), various offices within the Great Lakes Basin

Lipid Methodology

New micro-methods developed at GLERL to measure lipids in aquatic invertebrates were transferred to:

- National Water Research Institute, Burlington, Ontario
- Versar, ESM Operations, Columbia, MD

GLERL and Great Lakes Education

In conjunction with NOAA's desire to better inform the public of its research efforts, in FY 88 GLERL became involved in a number of Great Lakes community educational programs:

Partners For Excellence

In FY 88, GLERL became a partner with the Science Department of the Ann Arbor Public Schools in the school district's Partner's for Excellence Program (M.Quigley, T. Nalepa, GLERL Coordinators). The partnership seeks to enrich the curriculum of the public schools in the area of environmental science, particularly with respect to the Great Lakes and aquatic sciences. Designated Partnership activities include:

- Providing mentors to help students with Science Fair projects

- Providing practical "hands-on" experience to promising science-oriented students via participation in a Student Volunteer Program

- Providing information on careers in environmental science and acting as consultants for the science curriculum

- Inviting science teachers to laboratory-sponsored seminars.

Southeast Michigan Science Fair

In 1988, in conjunction with the Southeast Michigan Regional Science Fair, GLERL established and sponsored awards for Outstanding Projects in Aquatic Science in each of the Science Fair divisions: Senior Projects, Junior Projects, and Junior Models and Collections. GLERL staff (T. Croley, M. Quigley, D. Schwab, D. Reid, and A. Beeton) acted as general Science Fair judges and also as judges for the GLERL award.

Student Volunteer Program

GLERL and the Ann Arbor Public Schools have established a Student Volunteer Program authorized by the Civil Service Reform Act of 1978 (Public Law 95-454). This program will provide selected high school students with the opportunity to perform volunteer work at GLERL after school. Each participant will be assigned to a GLERL research scientist who will supervises the student's work and activities related to an active GLERL research project.

Facilities and Services

GLERL's research is conducted in a modern research facility with over 24,600 square feet of usable space, including 19 laboratories totaling 4,100 sq. ft., 990 sq. ft. of conference rooms, a 1,250 sq. ft. library, and 1,220 sq. ft. for computer resources. In addition to general laboratory equipment, GLERL has a fully-equipped low-level radio-isotope analysis laboratory, a stable isotope mass spectrometer (SIMS) laboratory added this year, several gas chromatographs and liquid scintillation counters, a high pressure liquid chromatography system, a multi-channel Coulter Counter, a full complement of growth chambers and incubators, stereo and inverted microscopes, and a fully equipped multi-purpose epifluorescence microscope.

We also maintain and operate a High Speed Microcinematography Laboratory housed in a temperature controlled environmental chamber. The combination of high-speed (500 frames per second) and precise control of the temperature between 1° and 30°C allows advanced studies of the feeding behavior of zooplankton over the broad range of temperatures found in the natural Great Lakes environment. In addition, a separate Cold Room is maintained for conducting experiments and growing biological cultures at low temperatures.

Computer Facility

The GLERL Computer Facility consists of a Local Area VAXcluster (LAVc) of eight VAX computers on site and the capability of accessing a Cyber 855 mainframe and a Cyber 205 supercomputer at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. GLERL is one of five remote nodes to the NIST facility, which is known as the Department of Commerce Consolidated Scientific Computing System (CSCS).

User terminals and microcomputers throughout the GLERL facility are hardwired to a communications switch that allows users to access the LAVc as well as the Cyber computers in Gaithersburg. Off-site access to the system is available through telephone lines and a private network that links NIST and all remote connections to the CSCS systems.

Over 80 accounts are supported for a variety of applications, including real time and near-real time data acquistion, data reduction, graphics, large scale modeling, statistical and mathematical analysis, telecommunications, and word processing.

Laboratory office automation and administrative/accounting, along with scientific applications, are supported by over 60 loosely networked microcomputers.

Library

The GLERL library staff provides library and related services in support of GLERL's research activities . A program-oriented research collection is maintained, with special retrieval services available when the existing collection cannot meet the needs of individual researchers. Library services include reference, interlibrary loan, photocopying, acquisition, circulation, and on-line information retrieval for laboratoryaffiliated personnel (Fig. 24). The GLERL library is open to the public for reference use only.

Collection holdings include 3,740 books, 4,180 unbound periodical volumes, and 3,035 technical reports in the areas of climatology, hydrology, hydraulics, ice, limnology, mathematical modeling, meteorology, oceanography, sedimentation, wave motion, contaminant organics, and nutrients, with emphasis on the Great Lakes Basin. Access to the collection of technical reports is supported by an interactive on-line search capability. GLERL library staff expedite on-demand document retrieval and provide expanded reference capabilities on behalf of GLERL scientists through direct access arranged with the Unversity of Michigan Libraries.

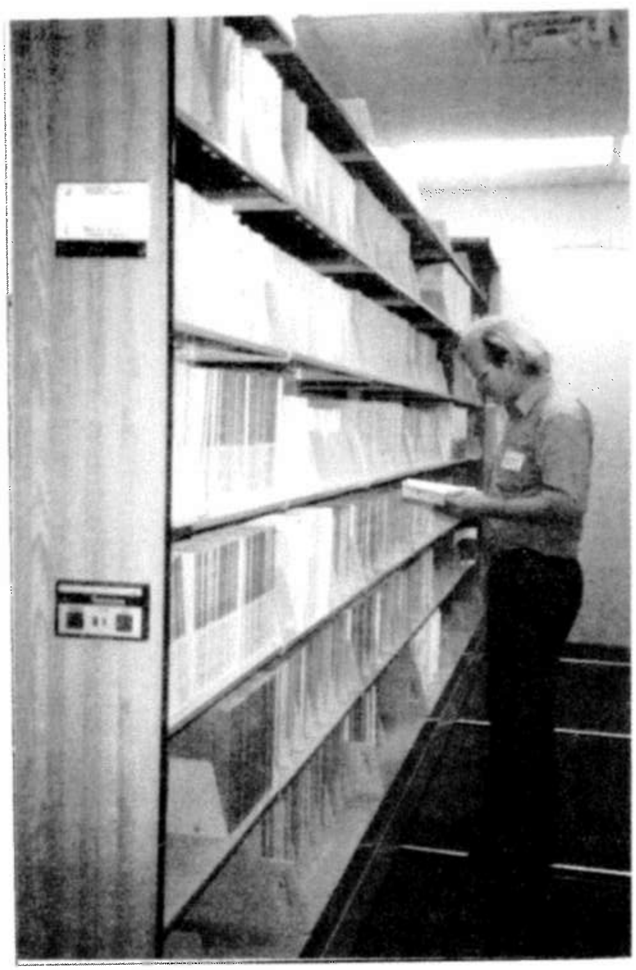


Figure 24. *The library's moveable shelving units allow for greater storage and easy access for GLERL staff and visiting scientists.*

The GLERL library is a member of the Michigan Library Consortium (MLC), Washtenaw-Livingston Library Network (WLLN), Federal Library and Information Network (FEDLINK), NOAA Library and Information Network (NLIN), and the On-line Computer Library Center, Inc. (OCLC).

During FY 88, the GLERL library acquired an OCLC M310 Workstation, which is an OCLC terminal that also supports dial-up access to other information systems, and can be used as a microcomputer to run third party software. The new workstation enhances the library's interlibrary loan, cataloging, and bibliographic searching capabilities.

The library receives 190 periodical titles in the year, while interlibrary loans increased nearly 50 percent. A local, on-line serials holding list is planned in FY 89 as well as an update of the library's holding in the Michigan Union List of Serials.

Marine Instrumentation Laboratory

The Marine Instrumentation Laboratory (MIL) staff selects, calibrates, repairs, and, when necessary, adapts or designs instruments to collect data in the lakes and their environs. The facility includes a woodshop, electronics design and maintenance shop and houses both the Cold Room and the Microcinematography Laboratory. Engineers and technicians in this unit work closely with GLERL researchers to ensure that instruments are compatible with their needs. MIL staff also participate in field experiments by providing support for the deployment and retrieval of field equipment, assisting with the collection of samples and data, and performing in-field maintenance or repair of equipment.

During FY 88, MIL engineers and technicians also worked to improve real time automated data return, and assisted with the resolution of problems related to GLERL's day-to-day operations of the facility. Their accomplishments include the following:

- Completion of operations support on the Gamma-scan automated two axis positioning system;
- Development of a prototype Lagrangian drogue recording system using LORAN navigation signals;
- Design and development of equipment used in the Green Bay Project for measurement of water movement and sediment transport;
- Detroit River monitoring using an RDDR-1200 Acoustical Doppler Current Profiler and a GOES reporting meteorological system. We have for the first time in history completely documented a flow reversal situation in the Detroit River;
- Captured data from the enhanced RDDR-1200 Profiler through bottom tracking, and with Dr. Schwab's assistance (PL&M Group), demonstrated its compatiblity for shipboard use in determining water transport.

Information Services - Publications Unit

The Publications Unit staff are responsible for providing editorial and publications support to the scientific staff, distributing GLERL publications, and responding to requests from the public for publications and information. They also produce and update brochures and informative fixed and portable displays concerning GLERL's work and/or important environmental issues.

During FY 88, the Publications Unit installed a Macintosh II - based desktop publishing system and Aldus Pagemaker software. The system includes a Postscript laser printer and a digital scanner. The new equipment allows for in-house preparation of camera-ready copy of NOAA generated documents, eliminates paste-up of black and white figures, and results in a cost savings at print time. The desktop publishing system permits completion of a variety of specialty jobs such as newspaper advertisements, announcements, graphics, award certificates, and typeset text for the portable displays.

For FY 88, the Information Services Group completed displays that were exhibited at the following events:

- The 31st Annual Meeting of the International Association for Great Lakes Research, held in Hamilton Ontario, Canada;
- The Air Toxics and the Great Lakes Conference sponsored by the Center for Environmental Study and the Michigan Office of the Great Lakes, held in Chicago, IL;
- The Great Lakes United Annual Meeting, held in Grand Rapids, MI;
- Extensive displays were made for GLERL's Open House, a public event that included a day of tours for classes from local schools, as well as a second day of tours for the general public. The National Weather Service, Michigan Sea Grant, and the Great Lake Commission also participated in the Open House.

Research products generated for FY 88 included 43 scientific articles, reports, and books, and 53 formal presentations. There were over 1,100 documented requests for GLERL information, with over 2,700 items mailed as a result of those requests.

The Publications Unit maintains, and updates eight mailing lists covering GLERL products. New NOAA-series publications are automatically distributed according to these mailing lists. All new publications, including journal articles and books, are added to our six-month update listing of new publications, which keeps our users informed of GLERL's latest product releases.

Research Vessel *Shenehon*

The *Shenehon* is owned and operated by GLERL. It is based at the U.S. Army Corps of Engineers' boat yard at Grand Haven, Michigan, and is the primary platform used in support of GLERL's open lake field investigations (Fig. 25). The vessel is 65.6 feet long, with a 6.5-ft mean draft, a 600-nautical-mile cruising range, and a 10-knot cruising speed. Navigational equipment include a Sperry Gyrocompass, Raytheon Radar, two LORAN-C units, a Sperry Auto Pilot, and a Raytheon Depth Sounder. A new LORAN-C system and a new 55-channel radiotelephone have been installed to improve the vessel's navigation and communication capabilities.

The *Shenehon* is a designated NOAA weather reporting station. In FY 86, the National Ocean Service installed a Shipboard Environmental (Data) Acquisition System (SEAS) aboard the *Shenehon*. The system includes equipment to record, process and plot water temperature data collected using Sippican Expendable Bathythermograph (XBT) probes. This system, the first in the Great Lakes, provides an increased capability to collect and transmit weather and water temperature data using satellite communications.

An electro-hydraulic articulated crane is available for the deployment and retrieval of water and bottom sediment samplers and heavy instrument moorings. Electro-hydraulic winches handle hydrographic wire and multiconductor cable for sample casts and in-situ measurements of water variables. An on-board laboratory is available for experiments and sample processing. Scientific equipment includes various sized water samplers, reversing thermometers, bottom samplers, including a box corer, and a 25 cm beam path transmissometer coupled to an electronic bathythermograph. A data acquisition system separate from the SEAS system records and plots data. The data are recorded in digital format.

Figure 25. *The R/V* Shenehon *is fully equipped for oceanographic studies and is the primary vessel used throughout the Great Lakes to collect the data used in most GLERL products.*

FY 88 Permanent Staff

	Full Time	Part Time	WAE
Office of the Director	11	3	0
Ecosystem and Nutrient Dynamics Group	9	2	2
Environmental Systems Studies Group	3	1	0
Lake Hydrology Group	10	2	5
Physical Limnology and Meteorology Group	10	3	3
Synthetic Organics and Particle Dynamics Group	8	4	2
TOTAL	51	15	12

Office of the Director
Beeton A.M. - Director
Noble, P.E. - Secretary
Reid, D.F. - Ass't to the Director

Administration
Mark, S.V. - Head
Lee, J.P.
Mull, R.C.

Computer Facility
Spalding, G.E. - Head
Del Proposto, D.J.
Fenton, J.F.
Herche, L.R.
Lefevre, J.T.
Shrum, A.F.

Information Services
Reid, D.F. - Head
Darnell, C.M.
Hubbard, B.D.

Environmental Systems Studies Group
Fontaine, T.D. - Head
Dillingham, L.E. - Secretary
Clites, A.H.
Lang, G.A.

Physical Limnology and Meteorology Group
Saylor, J.H. - Acting Head
Dillingham, L.E. - Secretary
Katt, G.A.
Laba, S.J.
Liu, P.C.
Lynn, E.W.
McCormick, M.J.
Miller, G.S.
Muhr, G.C.
Schwab, D.J.

Marine Instrumentation Laboratory
Soo H.K. - Head
Booker, H.L.
Dungan, J.E.
Kistler, R.D.
Lewis, C.A.
Miller, T.C.
Muzzi, R.W.

Ecosystem and Nutrient Dynamics Group
Gardner, W.S. - Head
Lojewski, N.L. - Secretary
Babbitt, M.T.
Fahnenstiel, G.L.
Gauvin, J.M.
Laird, G.A.
Liebig, J.R.
Malczyk, J.M.
Nalepa, T.F.
Quigley, M.A.
Scavia, D.
Tarapchak, S.J.
Vanderploeg, H.A.

Lake Hydrology Group
Quinn, F.H. - Head
Lawton, B.J. - Secretary
Assel, R.A.
Bolsenga, S.J.
Brook, J.R.
Croley, T.E., II
Darr, K.A.
Derecki, J.A.
Hartmann, H.C.
Hunter, T.S.
Kelley, R.N.
Leshkevich, G.A.
Makuch, L.L.
Norton, D.C.
Poorman, G.M.

Library Facility
Carrick, B.J. - Librarian
Threm, S.M.

Synthetic Organics and Particle Dynamics Group
Eadie, B.J. - Head
Mactaggart, I.R. - Secretary
Bell, G.L.
Chappell, J.L.
Faust, W.R.
Hawley, N.
Keilty, T.J.
Landrum, P.F.
Morehead, N.R.
Rivera, M.P.
Robbins, J.A.

R/V *Shenehon*
Morse, D.V. - Master Mate
Burns, W.R.
Grimes, J.E.

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CHANDLER, J.F., and G.L. FAHNENSTIEL. Partitioning of photosynthetic end products in Lakes Michigan and Huron. 31st Conference, International Association for Great Lakes Research, May 17–20, 1988, Hamilton, Ontario, Canada.

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DERECKI, J.A., L.L. MAKUCH, and J.R. BROOK. Unsteady flow model of entire St. Clair River. 31st Conference, International Association for Great Lakes Research, May 17–20, 1988, Hamilton, Ontario, Canada.

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HARTMANN, H.C., and F.H. QUINN. Climatic extremes and Great Lakes water management. Sixth IWRA World Congress on Water Resources, May 29–June 3, 1988, Ottawa, Ontario, Canada.

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LANDRUM, P.F., T.D. FONTAINE, B.J. EADIE, and W.R. FAUST. Prediction and uncertainty: field validation of a laboratory derived toxicokinetics model. Society of Environmental Toxicology and Chemistry, Eighth Annual Meeting, November 10, 1987, Pensacola, FL.

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LESHKEVICH, G.A. Clear-sky bidirectional reflectance measurements of freshwater ice using a sphere-scanning spectroradiometer. 31st Conference, International Association for Great Lakes Research, May 19, 1988, Hamilton Ontario, Canada.

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